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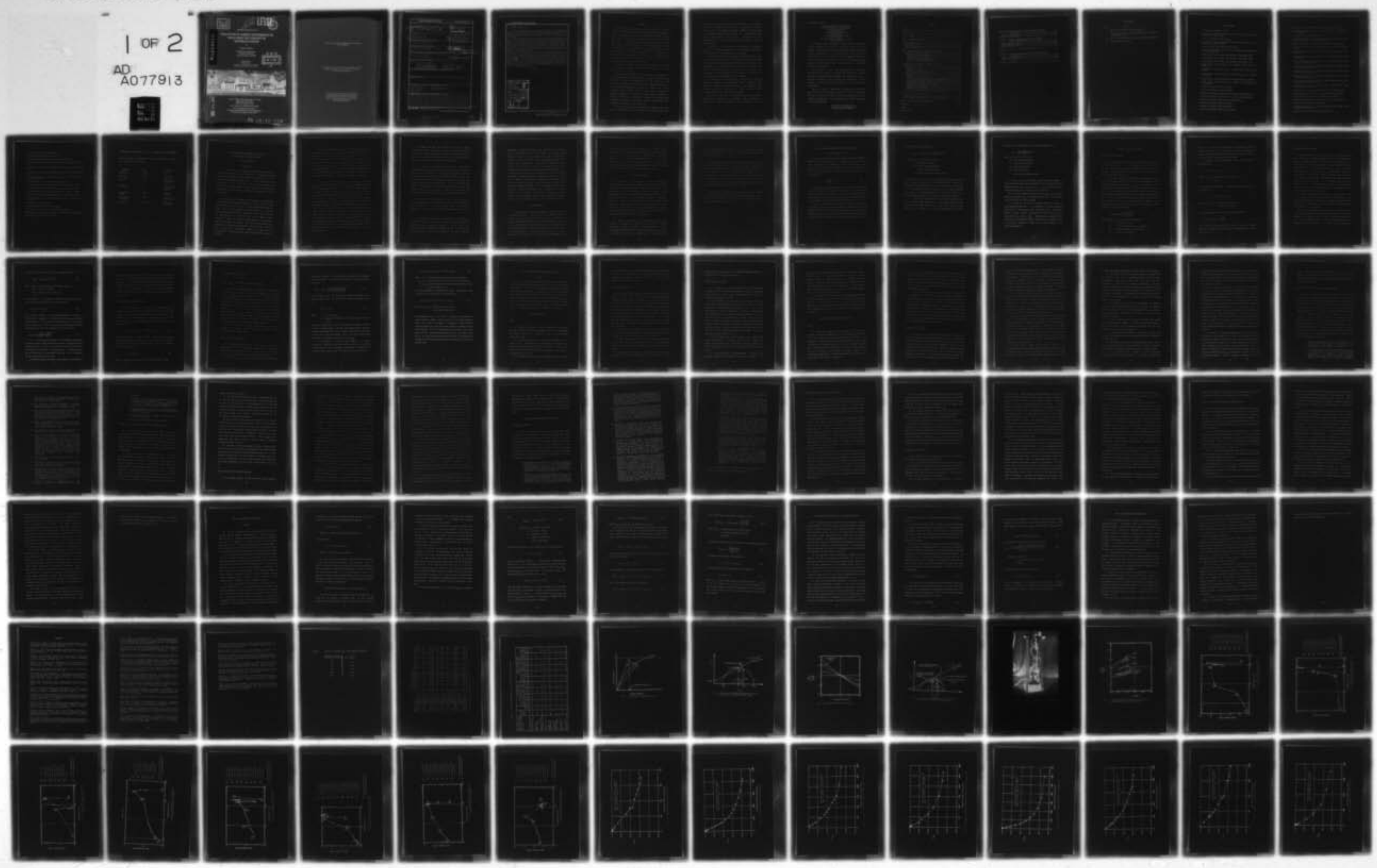

TECHNICAL REPORT GL-79-13

EVALUATION OF SAMPLE DISTURBANCE ON SOILS USING THE CONCEPT OF "REFERENCE STRAIN"

by

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Reference strain is a shear strain value that is obtained by dividing the shear strength by the initial tangent shear modulus. On a shear stress versus shear strain plot, it can be thought of as the shear strain at which the initial tangent shear modulus line, if extended, intersects the horizontal line through the point of maximum shear stress. If each shear strain value of a shear stress versus shear strain curve is divided by the reference strain and if each shear stress value is divided by the maximum shear stress, a normalized stress-strain curve is obtained. (Continued) over

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20. ABSTRACT (Continued)

For laboratory tests where undrained conditions exist or for other loadings such as in triaxial tests, it is possible to adjust the stress-strain data obtained on the basis of the type of loading and the *effective stress path* to obtain an equivalent, drained, normalized shear stress versus normalized shear strain curve.

Resonant column tests can most accurately measure the initial tangent shear modulus. An ultra sensitive, quasistatic torsional simple shear apparatus also can be used. It gives essentially the same values of initial tangent shear modulus on a given soil as does the resonant column apparatus which indicates that the initial tangent shear modulus is insensitive to strain rate. Extensive testing of a variety of normally consolidated or near normally consolidated, cohesive soils in this study shows that the initial tangent shear modulus is quite sensitive to sample disturbance, mean effective confining stress, and time in secondary compression.

Results of torsional simple shear tests and of triaxial compression tests give essentially the same normalized shear stress versus normalized shear strain curve. Use of reference strain provides normalized stress-strain curves which are independent of sample disturbance. These normalized curves may be used to establish insitu stress-strain behavior by making use of initial tangent shear moduli obtained in the field from seismic tests and by using undrained shear strengths (only needed for undrained field loading conditions) obtained by conventional field tests. This procedure utilizes the "sense" of the soil behavior from the normalized laboratory curve, and the "magnitude" of the behavior is obtained from field measurements.

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PREFACE

This report was prepared by Professor Vincent P. Drnevich, University of Kentucky, under Contract DACW39-78-C-0046 (Negotiated), as part of the on-going work at the U.S. Army Engineer Waterways Experiment Station (WES). The research was sponsored by the Office, Chief of Engineers (OCE), U.S. Army, under CWIS 31145 Work Unit entitled "Liquefaction Potential of Dams and Foundations during Earthquakes." The work was directed by Dr. W. F. Marcuson III, Research Civil Engineer, Earthquake Engineering and Geophysics Division (EE & GD), Geotechnical Laboratory (GL). General guidance was provided by Dr. P. F. Hadala, Chief, EE & GD, and Mr. J. P. Sale, Chief, GL. Mr. Ralph R. W. Beene, OCE, is the technical monitor for this CWIS work unit.

Directors of WES during this study and preparation of this report were COL John L. Cannon, CE, and COL Nelson P. Conover, CE. Technical Director was Mr. F. R. Brown.

Efforts on this research topic had begun at the University of Kentucky approximately ten months prior to the start of this contract with WES. The basic ideas associated with this research had been germinating for some time in the minds of the principal investigator and the co-principal investigator (Dr. Bobby O. Hardin). Dr. Hardin completed a state-of-the-art report in April 1978 on the Nature of Stress-Strain Behavior for Soils for the ASCE Specialty Conference in Pasadena (see HARDIN 1978 in References) and acted as a resource person throughout the contract. His ideas, comments and suggestions were invaluable for the execution of the project.

The topic of this research was an important element in attracting Dr. K. Rainer Massarsch to the University as a visiting professor from

Sweden where he was associated with the Royal Institute of Technology. A portion of Dr. Massarsch's support prior to and during the contract until his year at the University concluded in August 1978 was provided by the Swedish Building Research Council. Dr. Massarsch made many valuable contributions to the research, procured many of the Scandanavian soils, and was responsible for the resonant column tests reported herein.

Contributions to this problem prior to the contract with WES were also made by Dr. Ramkumar Beniwal, a post doctoral student sponsored by the Department of Civil Engineering at the University.

Two graduate students, Joseph P. Koester and Stephen H. Bickel were actively involved through most of the contract. Mr. Koester performed the torsional simple shear tests reported herein and was involved in the data analysis. In a similar fashion Mr. Bickel was involved with the resonant column/triaxial tests. The hard work, long hours, and contributions of these gentlemen are most appreciated. Both will use their results in writing theses for the M.S. degree.

The ingenuity and resourcefulness of the Laboratory Technician, Woodrow W. Thurman, are especially appreciated. Among many other things, he designed and built from scratch the controller for the torsional simple shear apparatus that allowed for either stress amplitude controlled or strain controlled testing.

No project of this nature can be executed without a wide variety of good quality "undisturbed" soil specimens. The contributions of specimens by a number of organizations and individuals need to be

acknowledged. They are:

Kentucky Department of Transportation
(Henry A. Mathis and Douglas Smith)
McClelland Engineers, Inc.
(Ronald J. Ebelhar)
Woodward-Clyde Consultants
(Faiz Makdisi)
Det Norske Veritas, Oslo Norway
(Rune Dahlberg)
Royal Institute of Technology of Sweden
(Bengt B. Broms)

The efforts of three undergraduate students need to be recognized. Johnson Toritsemotse and Charles Rivette were involved with data handling, manipulation and plotting including the writing of computer programs. Frances Wang, a part time secretary in the final four months of the project, not only mastered the use of a computer terminal and a text editing language but also typed this report (including equations) using this system and drafted many of the final figures. Her efforts have been truly remarkable.

The Department of Civil Engineering provided the laboratory facilities, the vast majority of the laboratory equipment, the computing terminals and data acquisition equipment and the principal and co-principal investigators salaries during the academic year. Without question, this has been a major contribution. It is most gratefully acknowledged.

Finally, the support, suggestions, and interest of the project's technical monitor, Dr. William F. Marcuson, III need to be recognized. His visit to the University during the project resulted in many helpful comments and suggestions. His time and effort in reviewing this report is sincerely appreciated.

Dr. Vincent P. Drnevich, P.E.
Professor of Civil Engineering
and Principal Investigator

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CONVERSION FACTORS, METRIC (SI) TO U.S. CUSTOMARY UNITS OF MEASUREMENT

Metric (SI) units of measurement used in this report can be converted to U.S. customary units as follows:

Multiply	By	To Obtain
millimeter	.0394	inch
milliliter	.0295	fluid ounces
kilopascal	.145	pounds (force) per square inch
megapascal	4.5	pounds (force) per square inch
millimeter per minute	.0394	inches per minute
kilogram per cubic meter	.0624	pounds (force) cubic foot
centistokes	1.08×10^{-5}	square feet per second

EVALUATION OF SAMPLE DISTURBANCE ON SOILS USING THE CONCEPT OF "REFERENCE STRAIN"

PART I: INTRODUCTION

Background

1. In June 1977, the National Science Foundation sponsored a workshop on "Research Needs and Priorities for Geotechnical Earthquake Engineering Applications" at the University of Texas (LEE et al. 1977). The workshop addressed seven topic areas. A list of research needs was established in each of these areas. Many of those expressed needs directly or indirectly related to the problem of sample disturbance, particularly as it affects the understanding and determination of insitu soil behavior.

2. More recently, a symposium on "Soil Sampling and Its Importance to Dynamic Laboratory Testing" (SILVER et al. 1978) was held at the 1978 Annual Meeting of ASCE in Chicago. The three state-of-the-act papers by Broms, Mori, and Horn reviewed the current knowledge of the topic in Europe, Japan, and North America, respectively. These reports point out the significance of the problem and show that the approach almost exclusively has been to improve sampling equipment and techniques, sample transportation and handling, and finally sample trimming and placement in test apparatus. Additionally, efforts have been to recreate insitu conditions by specialized laboratory loadings such as incorporated in the SHANSEP approach (LADD AND FOOTT 1974 and LADD et al. 1977).

3. Reducing sample disturbance has come to mean that sophisticated sampling techniques be used and that exotic laboratory testing be performed. The procedure is very expensive and results still turn out to be less than satisfactory. It is no wonder that many practitioners are forsaking laboratory results for empirical or semi empirical field tests. However, some field tests, especially those designed to obtain stress-strain behavior, e.g. self boring pressure meters (WROTH 1975) and high amplitude borehole dynamics tests (MILLER et al. 1975) can also be expensive and cumbersome. They also have significant limitations.

4. The nature of the problem of sample disturbance in cohesive soils has been illustrated in two classic papers (SKEMPTON AND SOWA 1963 and NOORANY AND SEED 1965). The key point made by these papers is that sample disturbance consists of two components, one associated with mechanical disturbance caused by the sampler, handling, etc. and the other is due to the release of total stresses. The term "perfect sample" is used to describe the sample that undergoes changes in stress but no mechanical disturbance. SKEMPTON and SOWA 1963 point out that the stress release (especially when soils are normally consolidated and insitu states of stress are anisotropic) significantly affects the undrained stress path but has little effect on undrained shear strength and virtually no effect on the shear strength parameters in terms of effective stress. The effect of mechanical disturbance is seen on both the undrained stress path and on the undrained shear strength but has very little effect on the shear strength parameters in terms of effective stress.

5. SKEMPTON AND SOWA 1963 attribute the change in behavior associated with sample disturbance to changes in the "micro structure" of the soil. It will be shown that the initial tangent shear modulus is sensitive to the change in behavior associated with sample disturbance because it is measured at non destructive strain levels.

6. In the early 1970's significant work was done (AFFIFI 1970, ANDERSON 1974) showing that shear modulus is significantly affected by time in secondary compression. It was suggested that the increase in shear modulus with log-of-time be determined with resonant column tests in the laboratory and that the modulus insitu be estimated from laboratory determined values extrapolated to the times since deposition insitu. This procedure has some obvious limitations but gives some rational basis for the differences between field determined and laboratory determined initial tangent moduli (ANDERSON AND WOODS 1975).

7. With the recent developments in the use of seismic methods for the insitu determination of initial tangent shear moduli (WOODS 1978), the practicality of the method proposed herein is increased. Furthermore, the effect of time on modulus is automatically accounted for.

8. The approach investigated in this project is different from previous ones in that it aimed at accounting for sample disturbance rather than trying to remove or eliminate it. An over view of the approach was given by DRNEVICH AND MASSARSCH (1978). The method makes use of conventional field as well as laboratory test data. Reasonably

undisturbed specimens are tested in the laboratory. The laboratory results are normalized by use of the concept of reference strain. Reference strain is a value of shear strain that is determined by dividing the maximum shear stress that can possibly be applied by the initial tangent shear modulus. Application of the concept involves dividing the shear stress values by the maximum shear stress and dividing the shear strain values by the reference shear strain. One of the goals of this project was to show that these curves are essentially independent of sample disturbance. Conventional field tests are then used to establish initial tangent moduli and shear strength insitu. These are then used to establish insitu stress-strain behavior from the normalized laboratory determined curve by inverting the process used to obtain the normalized stress-strain curve. Another way of expressing this process is to say that the laboratory tests describe the general behavior but that behavior requires field determined "calibration factors" in order to establish specific insitu stress-strain behavior.

Previous Research

9. The idea for this approach was generated from the work reported by HARDIN AND DRNEVICH (1972) which first describes the use of reference strain. It was found that for a given soil, normalized shear modulus (secant modulus divided by initial tangent modulus) varied with shear strain amplitude differently, depending on the confining stress. If, however, the values of shear strain amplitude were normalized by the use of reference strain, then a single curve could be used to describe the behavior of a given soil for all confining stresses. DRNEVICH (1975)

suggested that reference strain could be used to rationally describe insitu shear stress versus shear strain behavior. Continuing research at the University of Kentucky (HARDIN 1971, DRNEVICH 1972, HARDIN 1972, HARDIN 1978, and DRNEVICH AND MASSARSCH 1978) indicated the insensitivity of the normalized stress-strain (using reference strain) to sample disturbance caused by repeated loadings. The project reported herein is the first attempt to directly address the problem.

Scope of the Investigation

10. The purpose of this project is to study and evaluate the concept of reference strain for assessing effects of sample disturbance on normally consolidated cohesive soils. The first part of the investigation will be to demonstrate the nature and magnitude of sample disturbance. The torsional resonant column apparatus was used to test a variety of normally and near normally consolidated "undisturbed" specimens. Effects of stress history on the initial tangent shear modulus could be accurately monitored with this apparatus. Results from these tests could also be used to compare with measurement of initial tangent moduli measured on the same or similar specimens when tested in the quasi static torsional simple shear apparatus.

11. The next item involves the development of the theory and framework for analyzing the laboratory data. Although the general framework had already been applied to undrained loadings of cohesive soils (HARDIN AND DRNEVICH 1972), it was done without regard to changes in effective stress due to the applied shear. The procedures for

establishing normalized stress-strain data from simple shear and from triaxial data for drained or undrained stress paths were developed as a part of this project.

12. Two types of laboratory tests were performed to verify that the procedures established above were valid. The first involves both drained and undrained tests with the torsional simple shear apparatus. The second involves the use of a Hardin oscillator (HARDIN 1970) in conjunction with a conventional triaxial test. The Hardin oscillator provided values of initial tangent shear modulus for each point on the effective stress path. Both drained tests and undrained tests with pore pressure measurement were performed with this system.

13. Finally, the procedures for applying this process to establish shear stress-shear strain behavior insitu were established. The aims were to have a procedure that is both consistent and rational while also being simple enough to be practical.

PART II: THEORY ASSOCIATED WITH THE INVESTIGATION

Concept of Reference Strain

14. The concept of reference strain as first proposed by HARDIN AND DRNEVICH 1972 is illustrated in Fig. 1 which is a plot of shear stress versus shear strain. The intersection of the initial tangent shear modulus with the maximum shear stress occurs at a shear strain value which is termed the reference strain. Reference strain values are calculated from

$$\gamma_r = \frac{\tau_{max}}{G_{max}} \tag{1}$$

15. Normalized stress-strain behavior is obtained by dividing the shear stress values by the maximum shear stress and by dividing the shear strain values by the reference strain. The resulting curve has a shape similar to the original curve. The abscissa values range from zero to one hundred or more and the ordinate values range from zero to one.

16. The original use of the concept of reference strain was for cases where excess pore pressures generated by shearing were small or assumed to be small. The value of maximum shear stress was usually not measured but was calculated from the shear strength parameters in terms of effective stress assuming that no excess pore pressures were created.

The equation for the calculation is

$$\tau_{max} = [(p' \sin \phi' + c' \cos \phi')^2 - q^2_i]^{0.5} \qquad (2)$$

where: $p' = p'_i = 0.5[(\sigma'_1)_i + (\sigma'_3)_i]$

$q_i = 0.5\ [(\sigma'_1)_i - (\sigma'_3)_i]$

ϕ' = angle of shearing resistance in terms of effective stress

c' = cohesion in terms of effective stress

The subscript "i" in Eq. 2 refers to the "initial" state of stress which may be isotropic or anisotropic. For anisotropic states of stress, the maximum shear stress calculated by Eq. 2 is shown in Fig. 2. Note that it is the maximum applied shear stress and not the absolute maximum shear stress. The maximum applied shear stress will be equal to the absolute maximum only when the initial state of stress is isotropic.

17. The initial tangent shear modulus was usually measured by use of the resonant column apparatus or by very precise torsional simple shear apparatus at shear strains on the order of 10^{-3} percent or less. When it was not measured, it could be approximated by the Hardin

Equation. An improved version of this Equation (HARDIN 1978) is

$$G_{max} = \frac{625\ (OCR)^K}{0.3 + 0.7e^2}(P_a \sigma'_o)^{0.5} \qquad (3)$$

where: e = void ratio of the soil

OCR = Over Consolidation Ratio

K = coefficient from Table 1

P_a = atmospheric pressure

$\sigma'_o = (\sigma'_1 + \sigma'_2 + \sigma'_3)/3$

= mean effective confining stress

18. The value of initial tangent shear modulus was assumed to remain constant as shear stress was applied. This is consistent with the assumed pure shear stress path (see Fig. 2) since the mean effective confining stress does not change for such a stress path.

19. If both the maximum applied shear stress, τ_{max} and the initial tangent shear modulus, G_{max} are constant, then by Eq. 1, the reference strain is constant for a given loading.

20. In order for the concept of reference strain to be useful in assessing sample disturbance, it is necessary to establish consistent definitions of maximum applied shear stress and initial tangent shear modulus for other commonly used laboratory tests and for effective stress paths other than pure shear. The effective stress paths will be limited to those described by HARDIN 1978 as "Class 1 Loadings", where the deviatoric component of loading has a major influence on the resulting deformation.

Techniques for Special Loadings

Drained Pure Shear Loadings

21. For these loadings, the effective stress path is identical to the one assumed in Fig. 2 and the maximum applied shear stress is constant. The value of τ_{max} may be determined directly if the test is carried to failure (excursion from point (p'_i, q_i) to point (p'_i, q_f)) or may be determined from Eq. (2).

22. The value of G_{max} is best determined by measurement; applying cyclic shear strains less than 10^{-3} percent either quasistatically or by means of resonant column testing. If G_{max} is not measured for every stress point on the stress path (it would be relatively awkward to do so), it could be measured prior to beginning the shear and then adjusted for subsequent points on the stress path. The adjustments are based on Eq. (3). Since the effective confining stress remains constant for the entire stress path, G_{max} will only vary with the change in volume associated with dilation. Values of G_{max} for stress points of these drained tests can be estimated from

$$G_{max} = [G_{max}]_i \frac{0.3 + 0.7(e_i)^2}{0.3 + 0.7(e)^2} \qquad (4)$$

where: $[G_{max}]_i$ = G_{max} before shear loading begins

e = $e_i + (\Delta V/V)(1 + e_i)$

e_i = void ratio before shear loading begins

ΔV = volume change due to shear loading

V = volume of the specimen

Equation (4) has been used to prepare Fig. 3 which shows the effect of volumetric strain on G_{max}. In most typical tests, particularly for strains associated with the working stress range, volumetric strains are less than 2% and the correction can be neglected.

23. For each stress path increment, a shear strain increment is established from

$$(\Delta\gamma)_j = \gamma_j - \gamma_{j-1} \tag{5}$$

where: γ_j, γ_{j-1} = shear strains at stress point j and j-1

For this stress path increment, an average value of reference strain is calculated from

$$(\gamma_r)_j = 0.5[(\gamma_r)_j + (\gamma_r)_{j-1}] \tag{6}$$

where $(\gamma_r)_j$, $(\gamma_r)_{j-1}$ = reference shear strains at stress points, j and j-1

The normalized strain at stress point j is calculated from

$$(\gamma/\gamma_r)_j = (\gamma/\gamma_r)_{j-1} + \frac{(\Delta\gamma)_j}{(\gamma_r)_j} \tag{7}$$

The normalized stress-strain curve is obtained by plotting values of T/T_{max} for a given stress point versus the normalized shear strain as given by Eq. (7).

Undrained Pure Shear Loadings

24. When saturated or nearly saturated soils are subjected to pure shear loadings and undrained conditions exist or can be assumed to exist, the shearing action causes excess pore pressures to occur. Consequently, the effective stress path is no longer vertical but may be as shown in Fig. 4. For any given stress point, (p', q), along this effective stress path, the value of τ_{max} is determined by assuming the stress path to be vertical (pure shear) and passing through the stress point. Equation 2 is also used for determining this instantaneous value of maximum applied shear stress. For the undrained stress path, the value of p' in Eq. 2 is the abscissa value of the stress point on the stress path. Recall that in the drained test, p' was constant and equal to p'_i whereas for this case it is not.

25. Another advantage for defining the τ_{max} in this manner is that it is consistent with the value obtained for drained tests at the beginning of shearing before excess pore pressures are generated and it is consistent at failure where τ_{max} is identical to the applied shear stress required to cause failure.

26. The initial tangent shear modulus will also change for each point along the undrained effective stress path because the excess pore pressures cause changes in the mean effective confining stress (see Eq. (3)). It is recommended that the initial tangent shear modulus be measured at the start of the test. The values of initial tangent shear

modulus for any stress point, (p',q) is approximately given by

$$G_{max} = (G_{max})_i [\sigma'_o/(\sigma'_o)_i]^{0.5} \tag{8}$$

where: $(G_{max})_i$ = initial tangent shear modulus at (p'_i, q_i)

$\sigma'_o = [\sigma'_1 + \sigma'_2 + \sigma'_3]/3$

$(\sigma'_o)_i = [(\sigma'_1)_i + (\sigma'_2)_i + (\sigma'_3)_i]/3$

Quite frequently, the intermediate and minor principal stresses are equal for the initial conditions. For this situation,

$$(\sigma'_o)_i = p'_i - q_i/3 \tag{9}$$

For pure shear loadings, the intermediate principal stress, σ'_2 is affected only by changes in p'. The mean effective confining stress for these loadings can be calculated by an equation similar to (9) except that p' replaces p'_i. Thus, for the case of axially symmetric initial conditions and for pure shear loadings, Eq. (8) takes the form

$$G_{max} = (G_{max})_i \left[\frac{p' - q_i/3}{p'_i - q_i/3}\right]^{0.5} \tag{10}$$

27. It has been established that both the maximum applied shear stress and initial tangent shear modulus vary for undrained pure shear loadings. By Eq. (1) then, the reference strain must vary with each point along the stress path. Instantaneous value of reference strain for each stress point is determined by use of Eq. (1) in conjunction with Eq. (2) and Eq. (8) or Eq. (10).

28. Normalized shear stress-shear strain behavior is established by

performing an undrained shear test, recording the excess pore pressures along with the applied shear stress and resulting shear strain. For each data point, the stress path coordinates are determined and values of maximum applied shear stress, initial tangent shear modulus, and finally reference strain are determined. From this point on, the normalization procedure is identical to that for Drained Pure Shear Loadings starting in paragraph 23.

Undrained Triaxial Compression Tests

29. Like the stress path for undrained pure shear loadings, the stress paths for undrained triaxial compression tests will be curved and variable. The procedure for normalizing these data is similar to the procedure for the undrained pure shear loadings in that for each stress point, values of G_{max} are determined by use of equation (8), τ_{max} is determined from

$$\tau_{max} = c' \cos \phi' + p' \sin \phi' - q_i \tag{11}$$

Before normalization of stress-strain data can take place, the applied axial stress and the resulting axial strain must be converted to equivalent shear stress and equivalent shear strain. The equivalent shear stress is given by

$$\tau = 0.5\, \sigma_{axial} \tag{12}$$

where: σ_{axial} = axial stress applied to initial state of stress

and the shear strain is given by

$$\gamma = 1.5\ \varepsilon_{axial} \tag{13}$$

where: ε_{axial} = axial strain associated with σ_{axial}

30. The only unknown in applying this technique to triaxial data is the value of G_{max} at the start of the test. Several ways can be used to obtain G_{max} but the most convenient is to use a torsional resonant column device (HARDIN 1970) simultaneously with the triaxial test. (This was done for the triaxial tests performed in this research. They will be discussed in a later section.) Another way would be to use the Hardin Equation (Eq. (3)). Use of this equation, even though it only gives approximate values of G_{max} is superior to calculating G_{max} from the measured initial tangent Young's modulus unless this modulus is measured at axial strains on the order of 10^{-3} percent. (Such measurements are virtually impossible for conventional triaxial apparatus.)

32. Once the values of shear stress and shear strain are determined, the procedure is identical to that for Drained Pure Shear Loadings beginning in paragraph 23.

Drained Triaxial Compression Tests

33. Normalizing drained triaxial data are similar to that for undrained data except for a few minor differences due to the volume changes that take place during the test. These changes affect both the values of G_{max} and the determination of equivalent shear strain.

34. The value of G_{max} can be calculated from the value measured

before axial straining. This value must be corrected for both pressure and volume change. This correction is obtained by combining Equations (4) and (5)

$$G_{max} = [G_{max}]_i \frac{0.3 + 0.7(e_i)^2}{0.3 + 0.7(e)^2} \left[\frac{\sigma'_o}{(\sigma_o')_i} \right]^{0.5} \tag{14}$$

In the triaxial test, the initial mean effective confining stress, $(\sigma'_o)_i$ is given by Eq. (6) and the value during axial loading is given by

$$\sigma'_o = p' - q/3 \tag{15}$$

where: $q = q_i + 0.5\,\sigma_{axial}$

q_i = stress path ordinate for initial anisotropic state of stress

Because the application of axial load causes an increase in the mean effective confining stress, specimen volume changes during loading of normally consolidated soils will be greater in the triaxial compression test than in the pure shear loading. Hence, the void ratio will change more and as a consequence, so will the value of G_{max}.

35. Measurement of specimen volume changes or of lateral deformation is important if accurate normalized data are to be obtained from the triaxial test. If specimen volume changes are measured, the equivalent shear strain for the j-th stress point is calculated from

$$\gamma_j = \gamma_{j-1} + 1.5(\varepsilon_j - \varepsilon_{j-1}) + 0.5(V_j - V_{j-1})/V \tag{16}$$

where: γ_{j-1} = equivalent shear strain for (j-1)th stress point

ε_j, ε_{j-1} = axial strain for the j-th and (j-1) th stress points

V_j, V_{j-1} = specimen volumes for the j-th and (j-1)th stress points

V = initial specimen volume

If lateral deformation measurements are made, the equivalent shear strain for the j-th stress point is calculated from

$$\gamma_j = \gamma_{j-1} + (\varepsilon_j - \varepsilon_{j-1}) - [(\varepsilon_r)_j - (\varepsilon_r)_{j-1}] \tag{17}$$

where $(\varepsilon_r)_j$, $(\varepsilon_r)_{j-1}$ = radial strains for the j-th and (j-1)th stress points

The development of Eqs. (16) and (17) is based on the discussion of plastic dilation by HARDIN, 1978 and on the use of the Mohr diagram for strain. The process is analogous to calculating a tangent Poisson's ratio and applying it to the axial strain increment to determine a shear strain increment. The total shear strain for that stress point is the shear strain for the previous stress point plus the increment in shear strain. Once the shear stress-shear strain behavior is established, the procedure for obtaining normalized behavior is identical to that for the previous cases.

PART III: TESTING EQUIPMENT, PROGRAMS, AND RESULTS

General

36. Three different test apparatus were used in this research: Drnevich torsional resonant column apparatus, Kentucky torsional simple shear apparatus, and a triaxial apparatus that incorporated a Hardin oscillator. Associated with each apparatus is a testing program which was designed to accomplish specific objectives. In this part of the report, each apparatus is described, the testing procedures are given, a summary of the soils tested is presented and typical results are shown. Also, a brief analysis of the results is made. The computer programs referred to in this part are located in appendices of the report.

Resonant Column Test

General

37. The Resonant Column Test is used to determine the shear modulus and shear damping of cylindrical specimens of soil in the undisturbed and remolded conditions. In this series of tests, only undisturbed samples were tested.

38. The modulus and damping of a given soil as measured by the resonant column, depend upon the strain amplitude of vibration, the ambient state of effective stress, and the void ratio of a soil as well as other factors such as stress history, time effects, soil structure, overconsolidation ratio, etc.

39. The purpose of these tests was to establish values of initial

tangent shear moduli for use in the normalization process. In addition, the effects of consolidation time, confining stress history and vibratory strain history were also obtained for these normally consolidated, naturally occurring soils.

Description of Apparatus

40. A Drnevich torsional resonant column apparatus (See Fig. 5) was used for the tests reported in this section. A sinusoidal torsional vibration excitation device was attached to the active end platen while the passive end platen was fixed. Solid cylindrical specimens with diameter of 50 mm (2.0 inch) and length of 100 mm (3.9 inches) were used for all tests. Filter paper strips were used to facilitate drainage and pore pressure equalization. Double membranes were used to enclose the specimen and water was used as a confining medium. An air-water interface existed above the O-rings on the upper platen. The torsional drive head was not submerged. Regulated compressed air was used to apply confinement.

41. Volume change was measured by use of burettes connected to the lower platen. Back pressuring was achieved by applying regulated compressed air to the air-water interfaces in the burettes.

42. Pore pressures were measured by a pressure transducer built into the lower platen and specimen length changes were monitored with a Linear Varying Differential Transformer (LVDT) located within the chamber.

43. Apparatus calibration and data reduction were done according to the procedures outlined by DRNEVICH 1978. The calculations for data

reduction were all performed by use of a FORTRAN program called RC-5, a listing of which is provided in Appendix A.

Testing Sequence and Results

44. Specimens were first consolidated and then backpressure saturated. If the backpressuring had been done first, the specimens would have had a chance to swell and associated with this is the likelyhood of additional disturbance.

45. The consolidation was carried out in two steps with the initial tangent shear modulus being measured as a function of time in each step. Usually, each confining stress was maintained for at least one log-cycle-of-time into secondary compression. The values of initial tangent shear modulus at the end of primary consolidation are given in Fig. 6. The slopes of the lines connecting the two points range from 0.3 to 0.63. According to the Hardin equation (Eq. (3)), the slope should be 0.5 when corrected for changes in void ratio. Slopes much less than 0.5 indicate that the soil is preconsolidated for those stress levels. Note that the effective confining stresses are relatively low for all specimens (less than 100 kPa (15 psi)).

46. The loading history of each specimen in the resonant column test is given in Figs. 7 through 14 where the initial tangent shear modulus is plotted versus the elapsed time from the beginning of the test. The significant points in the testing process are noted in each figure.

47. After consolidating and backpressuring, each specimen was allowed to stabilize for a period of time (usually overnight). Then

large amplitude vibratory strains were applied in increasing amounts until the limit of the apparatus was reached. The effects of large amplitude vibration are clearly evident in Figs. 7 through 14 and the results of normalized secant shear modulus versus normalized shear strain amplitude are given in Figs. 15 through 21. Values of initial tangent shear modulus and τ_{max}, for each test, were assumed constant. Values of these are given on the figures.

48. These test results show that the initial tangent shear modulus is sensitive to changes in total stress, effective stress, and strain amplitude, all of which occur in even the most careful sampling operations. The resonant column test can also be used to give accurate initial tangent moduli for use in the normalization process proposed in this report.

Quasistatic Torsional Simple Shear Tests

General

49. These tests utilized a special apparatus developed at the University of Kentucky by HARDIN 1971. It was available for this project at no cost except that extensive modifications were made to the apparatus to accommodate softer soils and to increase its accuracy and flexibility. The apparatus rotates the top of a cylindrical specimen that is fixed at the bottom. The sample is enclosed in a rubber membrane and has a confining stress applied in a fashion identical to a conventional triaxial test. Detailed information on this apparatus is given later in this section of the report.

50. Two test programs were carried out with this apparatus. The first was on a number of the same soils tested with the resonant column apparatus discussed previously. The purposes of these tests were to obtain accurate normalized shear stress-shear strain data for these soils and secondly, to show that the normalized curves are relatively independent of disturbance.

51. The second test program was on a remolded soil. The purpose of the program was to isolate the effects of sample disturbance and effective stress path. To do this, two types of tests were performed on nearly identical specimens. One set of tests was performed on saturated specimens with no drainage permitted. Measurement of pore pressures made it possible to establish the corresponding effective stress paths. The other set of tests, on specimens nearly identical to those used in the first set, was drained tests run slowly enough to allow all excess pore pressures to dissipate. The same soil was also used in the triaxial test program which will be described later.

Description of Apparatus

52. An overview of the Kentucky torsional simple shear apparatus and its accompanying electronics are given in Fig. 22. A close-up view of the components within the pressure chamber are given in Fig. 23. Only a small portion of the 50 mm (2.0 inch) diameter by 79 mm (3.11 inch) length specimen can be seen in this photo because the specimen is nearly surrounded by a frame which rigidly clamps the upper platen during assembly of the apparatus. A second frame (visible in the foreground) supports two Linear Varying Differential Transformers (LVDTs). The

cores of the LVDTs are suspended by very soft springs and impinge on arms attached to the top platen. A torque transducer is also attached to the top platen. Torque is applied by a gear motor and gear reduction system which is shown in Fig. 24. This system is attached to the rods that secure the pressure chamber lid and the torque is transmitted to the torque transducer by means of a stainless steel shaft that passes through a bushing and bearing system in the pressure chamber lid.

53. A reversible, variable speed motor was used as a source of torque. A special electronic control was constructed which reverses the motor at any preset level of torque (stress amplitude control) or of rotation (strain control) of the specimen top platen. The gear reduction is either 10^5 to 1 or 8×10^6 to 1 depending on whether or not an extra two gears are employed. Frequencies of loading can easily be adjusted from 0.5 cycles/second to approximately 0.2 cycles/day.

54. Torque and rotation are both measured inside the chamber. Shear stress is calculated from the torque assuming a linear variation of shear stress across the radius of the specimen. If the other extreme, uniform shear stress across the specimen is assumed, the relationship between torque and shear stress only varies by 12 percent. The most correct relation between torque and shear stress is shear strain dependent and lies between the two extremes. For the purposes of this research, it was felt that the linear assumption would provide sufficiently accurate results.

55. Shear strain is related to the rotation of the top of the specimen and is based on a linear variation of strain with radius. The shear strain values reported in this research are based on the average shear strain energy in the specimen and are consistent with the shear

strains conventionally reported for torsional resonant column testing.

56. The specimen has filter paper strips around its perimeter (two are visible in Fig. 23) to facilitate drainage and pore pressure equalization. Porous bronze filter disks with razor blade vanes protruding 2 mm (0.08 inch) are fastened to each platen. The lower platen has connections to the volume change/back pressuring system and contains a differential pressure transducer. The other side of this transducer is connected to the pressurized air that applies confinement. The output of this transducer is a measure of the effective confining stress in the specimen.

57. Two membranes were used to enclose the specimen. The membranes and platens are submerged with silicone oil to restrict air migration into the specimen. The oil used is Dow-Corning 200 Fluid, a dimethyl-polysiloxane having a viscosity of 100 centistokes. It is inert and harmless to membranes.

58. Axial deformation of the specimen is monitored with another LVDT located outside the chamber. It measures the vertical movement of the stainless steel rod that transmits the torque from the gear reduction system to the torque transducer.

59. A second pressure transducer is installed in the chamber base to monitor the chamber pressure. The maximum working chamber pressure is 700 kPa (100 psi).

60. Volume change measurements are accomplished by means of various capacity burettes attached to the lower platen. The tops of the burettes are attached to a regulated compressed air supply for backpressuring.

61. All transducers are connected to signal conditioning electronics which are in turn connected to a computer controlled data

acquisition system that applies calibration factors and calculates the desired engineering parameters. All data are both printed out and are stored on magnetic tape. The stored data are subsequently combined with data from other portions of the same test or with data from other tests and automatically plotted.

62. The conditioned rotation and torque signals are also supplied to an X-Y pen recorder. These records are proportional to the strain-stress behavior in the sample. Typical recordings are given in Figs. 25 and 26 which are taken directly from the X-Y recorder. At shear strains of approximately 2 percent, the LVDTs used in measuring rotation could no longer follow the deformation. Beyond that range, shear strains were estimated by use of elapsed time and rate of rotation which was constant. (The apparatus is currently being modified to measure these rotations directly.) Note that the specimen is near failure at a shear strain of 2 percent. The loss of the LVDTs for measuring strains beyond 2 percent accounts for the nearly vertical unloading portion of the curve. Loading in the opposite direction could only be carried to 2 percent shear strain because the LVDTs prevent further straining in that direction.

63. Two types of loading are performed in the course of testing: low amplitude cyclic loading at 1/10 cycle per second and long term, static cyclic loading. The former is used to obtain the values of G_{max} at shear strains on the order of 10^{-3} percent and the latter is used to obtain detailed data for points along the stress-strain curve (to failure, if desired). Separate data acquisition programs are used for each type; SADCYC.BB for the G_{max} determination and SADLT. BA for the stress-strain behavior. Both are contained in Appendix B. A third

program, NORMAL.BA (also given Appendix B), is used to provide normalized stress-strain information. It recalls the data stored by SADLT.BA and requires values of G_{max} and shear strength parameters to be input from the keyboard.

Torsional Simple Shear Testing of Undisturbed Samples

64. Eight of the soils tested in the resonant column tests were also tested in the "undisturbed" phase of this project. The torsional simple shear device was set up for strain-control tests. The majority of samples tested were previously used in a resonant column testing program, and were carefully retrimmed to conform to the shorter sample length requirements of the torsional simple shear apparatus. As a result of the prior testing, the samples were subjected to an initial disturbance, and hence were not precisely representative of insitu material. Although the ideal situation would have been to use a completely undisturbed soil for the shear testing sequence, the shear strain levels imposed by the resonant column tests were low (usually less than 0.1%). Besides, the resonant column tests measured changes in soil behavior by use of G_{max} measurements throughout testing. The steps in the testing program are as follows:

(1) The sample was trimmed to conform to the geometry of the torsional simple shear device: sample length = 79 mm (3.11 inches), sample diameter = 50 mm (2.0 inches). Sample weight and water content were determined.

(2) The trimmed sample was placed on the porous disk attached to the lower platen. The top platen with attached porous disk was placed on the specimen. The specimen was then surrounded by filter paper strips. Two thin rubber membranes were placed by use of a membrane expander. Double O-rings completed the seal between the membranes

and platens. The pneumatic clamp was bolted into place. Application of pressure to the pneumatic cylinders caused the top platen to be rigidly held.

(3) Upon completion of apparatus assembly, a confining pressure of 30 kPa (4 psi) was applied to the sample, drainage was prevented, and the clamp was released.

(4) The effective overburden stress insitu was estimated from the boring logs and a confining stress equal to 1.5 times this value was applied. (In several cases, it was suspected that the soil was preconsolidated insitu. For these cases, the confining stress applied was 1.5 times the estimated preconsolidation stress.

(5) During the consolidation process, periodic quasi-static cyclic torsional simple shear tests were performed as often as time permitted, to monitor the behavior of the initial tangent shear modulus, G_{max}.

(6) Consolidation was allowed and G_{max} testing performed to a minimum of one log-cycle into secondary compression.

(7) Saturation of the specimen was assured by backpressuring using 50- kPa increments. The "B" pore-pressure coefficient was determined for each cell pressure increase and values greater than 0.95 were deemed adequate. Minimum backpressures were arbitrarily set at 3 times the estimated insitu pore pressure and the maximum for the system was 400 kPa (58 psi). G_{max} testing was performed at each step in the backpressuring operation for two reasons: to obtain the initial tangent shear modulus and to free any adhesions in the axial mechanism of the torsion apparatus, which might inhibit length changes and adversely affect effective stress measurements.

(8) The consolidated and backpressured specimen was left to stand overnight.

(9) Following an overnight rest, G_{max} was again determined and it was determined again just prior to the first large-strain amplitude shear testing.

(10) Drainage valves were closed and the large-amplitude shear test was run to limits of rotational measurement each direction (shear strain of +/- 2%) and returned to zero stress-zero strain conditions. The rate of strain was set to ensure adequate pore pressure equalization throughout the specimen. A typical rate for this phase of testing was 0.11 percent shear strain per minute.

(11) Immediately following the undrained large-strain test, G_{max} was determined by low-amplitude cyclic shear

testing.

(12) Pore water drainage valves were opened and the specimen was allowed to reconsolidate to the same initial effective confining stress. Once again G_{max} was monitored as often as time permitted until the specimen was at least one-log cycle into secondary compression.

(13) G_{max} was determined just prior to a second large-strain amplitude shear test, where the procedures of steps (10) and (11) were repeated.

(14) A final set of apparatus readings is taken, and the device was dismantled.

(15) The post-test soil properties were determined.

Test Results for Simple Shear Tests on "Undisturbed" Specimens

65. To illustrate the nature of the data, results from tests on Valen clay, a soft sensitive clay from Gothenberg, Sweden will be used. The properties of this soil are given in Tables 2 and 3, and the results are plotted in Figs. 27 through 30. In each of these figures, the data points denoted by circles are for the first shear test applied to the specimen and the diamond points are for the second test performed after reconsolidation.

66. In Fig. 27, the effective stress paths are shown. The sloping line corresponds to a condition of failure with the effective angle of shearing resistance of 23 degrees. In this case, the once tested soil was reconsolidated to an effective confining stress slightly higher than the "undisturbed" soil. This was caused by drift in the air pressure regulators. Note that the two effective stress paths are somewhat similar but that the "disturbed" and reconsolidated soil exhibited more positive excess pore pressures than did the "undisturbed" specimen. (It has been long recognized that disturbance affects the undrained

effective stress path behavior.)

67. The shear stress versus shear strain is presented in Fig. 28. Note that the shear stress for the "disturbed" and reconsolidated soil is lower than the shear stress for the "undisturbed" soil even though the former was reconsolidated to a slightly higher confining stress. The secant shear moduli associated with these tests are given in Fig. 29. The initial tangent shear modulus is significantly lower for the "disturbed" and reconsolidated specimen.

68. When the data of these tests are normalized by use of reference strain according to the procedure outlined in Part II of this report, the two curves essentially reduce to a single curve as shown in Fig. 30. Normalized shear stress versus normalized shear strain for the other soils tested are given in Figs. 31 through 34. Values of G_{max} for the initial part of each curve are given in Table 3. Values of τ_{max} used in normalizing these data are based on values of angles of shearing resistance as given in Table 3.

69. There were cases where comparable effective confining stress and consolidation time conditions existed between these torsional simple shear tests and the previously reported resonant column tests. Initial tangent shear moduli data from both apparatus are compared in Fig. 35. It can be concluded that both tests give essentially the same values even though one apparatus is run at 0.1 Hz. and the other at 30 or so Hz.

Simple Shear Testing of Remolded Specimens

70. The primary objective of these tests was to show that the

normalized stress-strain curve is independent of effective stress path. Four tests on nearly identical remolded specimens were performed. Details of the soil and preparation procedures are given in Appendix C. The effective confining stresses for each of the tests were 63 kPa, 94 kPa, 127 kPa, and 100 kPa, respectively. The first and last tests were run at a shear strain rate of 0.005 percent/min and full drainage was allowed. The stress paths for these test were vertical and are shown in Fig. 36. The other two tests were run at 0.006 percent per minute but drainage was not permitted and excess pore water pressures were measured (actually, effective stress was measured directly by use of the differential pressure transducer which was described earlier). The effective stress paths for these two tests are also shown in Fig. 36.

71. The procedure for testing was nearly identical to the procedure described earlier for the tests on undisturbed samples except that backpressuring was done before consolidating, the rate of loading was slower for these tests and larger strains were applied in the first quarter cycle of loading. The effect of these procedures on the initial tangent modulus was measured and a typical test is shown in Fig. 37. Primary consolidation was complete in about 100 minutes in these tests. The specimen was allowed to remain in secondary compression overnight before the application of large shear strains.

72. The data acquisition system malfunctioned through the last segment of the high amplitude phase of each test (shear stress values abruptly became inordinately large) and the data were taken manually from the voltmeter readings. At first it was thought that the data were unaffected by the malfunction. But when the data were compared with those of the triaxial/resonant column tests (these will be presented

subsequently), it was found that the angle of shearing resistance was 27^{o} whereas the triaxial data gave an angle of 36^{o}. According to tests on clays reported by SAADA *et al.* 1978, the torsional simple shear data gave significantly larger angles of shearing resistance than did the triaxial tests. Furthermore, the initial tangent shear moduli were only 60 percent of those obtained by the triaxial/resonant column tests (See Fig. 38). When the torsional simple shear tests were run on the undisturbed soils, the values of initial tangent shear moduli were nearly identical with those obtained by the resonant column (See Fig. 35). It is believed that the initial tangent shear moduli from the triaxial/resonant column tests are the correct values because the resonance method is more accurate and because they compare extremely well with the Hardin Equation (Eq. 3) which is also plotted in Fig. 38.

73. The shear stress-shear strain curves for these tests are given in Fig. 39. In each of these tests, the shear stress is still slightly increasing at shear strains of 4 percent. One technique that is useful in obtaining the shear strength is to plot the ratio of shear strain to shear stress versus shear strain as is done in Fig. 40 for data from test SP-5. The inverse of the slope of the straight line fitted to the data gives a good estimate of the shear strength. This technique is commonly used and assumes that behavior is hyperbolic. It is recommended that the most weight be given to data in the range of strains from two to four percent when the data give a line with some curvature.

74. One very interesting fact associated with these tests is that the normalization process removes the problem of possibly incorrect shear stress calibration because the shear stress calibration is used in

determining both shear strength and the initial tangent modulus. Normalized stress-strain data are presented in Fig. 41 for these tests. Data from the four tests give essentially the same normalized curve and it can be concluded that at least for this soil and these stress paths, the normalized stress-strain curve is independent of effective stress path.

Triaxial Compression/Resonant Column Tests

Description of Apparatus

75. The test apparatus used in this phase of the program is shown in Fig. 42. It is essentially a triaxial test apparatus with a device for providing low amplitude dynamic vibrational loading to the sample. The main components are: a) the vibration excitation device, b) support for the vibration excitation device, c) top and bottom platens, d) the triaxial cell assembly, e) electronic measuring devices for recording the response to static and dynamic loadings, f) the control and readout instrumentation, g) the burette system with drainage lines, h) the axial loading press, i) the pressure system.

(a) The Vibration Excitation Device - The dynamic loading was accomplished by the use of a Hardin oscillator (HARDIN 1970) as shown in Fig. 43. This device applied a torsional vibration to the top platen of the specimen. The vibration was sinuoidally varying with time; the frequency and amplitude of vibration were adjustable.

(b) Support for the Vibration Excitation Device - The oscillator had to be continuously supported throughout the test to prevent unwanted compression of the specimen. To accomplish this, two methods of support for the device were needed. During the test setup a pneumatic cylinder support was utilized (see lower portion of Fig. 44). This

system supported the weight of the oscillator by the extension of piston rods when air pressure was applied to the pneumatic cylinders. During the test, the piston rods were withdrawn to allow for axial movement of the oscillator and support was provided by a counterbalance assembly connected to the axial loading piston that passed through the triaxial chamber lid.

(c) The Specimen Cap and Base - These elements, also known as the upper and lower platens were 5 cm (2 inches) in diameter and were machined from stainless steel and fitted with bronze filter disks. The disks were of sufficient roughness to ensure complete coupling between the specimen and the platens. The lower platen was provided with ports and fittings for the drainage and saturation lines. A pressure transducer was also connected to this lower platen.

(d) The Triaxial Cell Assembly - With a few exceptions this apparatus was similiar to commonly used triaxial cells. The plexiglass chamber and tie rods were longer than typical. The purpose of this was to accomodate the Hardin oscillator and wiring within the cell. A second difference was the top plate of the triaxial chamber was provided with electrical fittings to allow the signals between the instrumentation and the oscillator to be transferred through the chamber.

(e) The Electronic Measuring Devices - The measuring devices included: 1) a length change LVDT for reporting the specimen axial deformation, 2) a load cell mounted with the oscillator for measuring the axial load, 3) a differential pressure transducer connected between the chamber fluid and the pore water to give readings on the effective stress within the sample, 4) an acceleration transducer that produced an electrical output in proportion to the specimen cap rotational acceleration.

(f) The Control and Readout Instrumentation - For the dynamic loading and response measurement the following instruments were used: 1) a sine wave generator was necessary to provide the vibration excitation device with a sinusoidally varying power, 2) a power amplifier was connected in series with the sine wave generator for the purpose of amplifying the sinusoidal current to the level required for sufficient rotational displacement of the top cap, 3) a frequency counter displayed the frequency of vibration for the top cap, 4) a charge amplifier conditioned the voltage output from the acceleration transducer, 5) an X-Y oscilloscope was utilized to visually display the values for acceleration versus power; resonant frequency was accomplished when the power and acceleration signals were 90^{o} out of phase of when the trace appeared as a vertical ellipse, 6) two voltmeters

gave readouts for the voltage supplied to power the oscillator and the voltage provided by the acceleration transducer.

For the static loading and response measurement, the instrumentation included: 1) three signal conditioning devices, one for the axial deformation LVDT, one for the load cell and one for the effective stress transducer were required. The signal conditioning was needed to amplify the measuring devices output voltage to a level of maximum readout response and also keep the output signals within limits dictated by the data acquisition system specifications, 2) three voltmeters were used to display voltages in proportion to the measured values of axial deformation, axial load, and effective stress.

(g) The Burette System - This system consisted of two glass burettes, having different diameter, a storage reservoir, and the necessary plumbing. The large burette could be read to the nearest 0.5 ml (0.015 fluid ounces). It was used during the saturation phase of the test. During consolidation ard the application of the axial load flow was diverted to the small burette. This one could be estimated to the nearest .01 ml without difficulty. The drainage lines were 1.6 mm (1/16 inch) I.D. rigid plastic tubing. It was felt that practically no expansion occurred at working pressure levels in this testing.

(h) The Load Press - To apply the axial load a screw-type gear driven triaxial press was used. This type of press provides a constant strain rate during the test. A wide range of strain rates was possible and values from 1.24 to 0.0003 mm/min (.049 to .000012 in/min) could be accomplished by changing the driving gear ratios.

(i) The Pressure System - Regulated compressed air was the means for providing confinement to the specimen, regulating valves, a dial gage, and the plumbing associated.An air-oil interface existed inside the chamber where an inert silicone oil (the same as used in the torsional simple shear tests) covered the membrane enclosed specimen. The maximum chamber pressure was 700 kPa (100 psi). Regulated compressed air, acting on water levels in the volume change burettes was used for back pressuring.

76. Calibration of the apparatus for resonance testing was according to the procedures set forth by DRNEVICH 1978.

Procedure for Data Acquisition and Reduction

77. The data from these tests are divided into two categories; static data and dynamic data. For each point along a stress path, the static data values recorded included: cell pressure, effective stress, axial load, axial deformation, and burette readings. The dynamic values measured were: torque, acceleration, and resonant frequency. The elapsed time was also recorded.

78. All data were taken manually with the sampling intervals ranging from one or two minutes in the initial portion of the tests to several hours or more near failure. In addition, the values for effective stress, axial load, and axial deformation were taken automatically by a Digital Equipment Corporation, PDP-8 Minicomputer data acquisition system. This was helpful for it provided an easy and quick means to compute axial strain, principal stress ratio, and effective stress point coordinates while the test was running. The PDP-8 ran a BASIC program named TRIAX.KA to acquire and reduce this static data. A copy of this program is included in Appendix D.

79. Each page of data contained up to eighteen data sets. The pages were used to create data files that were stored in the University's IBM 370 computer. After all of the files were stored, the measured data were ready to be reduced. For this purpose a FORTRAN IV program named RC6B was used. This program was written by Dr. V. P. Drnevich and revised by S. H. Bickel to conform with the needs of this research. A copy of RC6B is given in Appendix D along with its accompanying subroutine RCSUB. This subroutine essentially consists of the FORTRAN program provided by DRNEVICH 1978.

80. Using the measured data RC6B returned values for axial strain, principal stress ratio, void ratio, dynamic shear strain, dynamic shear modulus, damping ratio, and effective stress point coordinates. Because the dynamic strain was kept from exceeding 0.001%, the dynamic shear modulus was the initial tangent shear modulus, G_{max}.

81. The computations involved for reduction of the static data are typical for the common triaxial test. The method of calculation of the dynamic data is well outlined in other sources (DRNEVICH, 1978).

82. During the analysis, it was necessary to calculate a normalized shear stress-strain relationship for the drained tests. In order to accomplish this a BASIC program named KARDUF.A1 was written by S. H. Bickel. This program calculated shear strain based on an instantaneous Poisson's ratio and incremental axial strain. The input data parameters were burette reading, axial strain, G_{max}, and effective stress point coordinates. The program returned values for normalized shear stress and normalized shear strain using the theory given earlier in this report.

Description of the Testing

83. Each test was run in five phases. They were: setup, saturation, consolidation, load application and takedown.

84. The test setup was concerned with placing the remolded specimen in the apparatus while causing minimum sample disturbance. The procedure used is described very completely in the literature (HARDIN, 1970) and (DRNEVICH, 1978). After the apparatus was assembled, a seating pressure of 20 kPa (2.8 psi) was applied to the specimen.

85. With the application of the seating stress, backpressure

saturation began. Backpressuring preceded consolidation in these tests because remolded specimens were being tested. The cell pressure was raised to 120 kPa (17 psi) and the increase in effective stress was noted. The "B" pore pressure coefficient was calculated. The back pressure was raised to 100 kPa (14.5 psi) and the drainage line was opened to allow water under the backpressure to flow into the sample. After several hours, the drain value was closed, the cell pressure raised 100 kPa (14.5 psi), a value for "B" computed, and the back pressure similiarly increased. This process was carried out in 100-kPa increments until the cell pressure was 420 kPa (61 psi). At this point the sample was allowed to saturate overnight under a backpressure if 400 kPa (58 psi). The "B" coefficient generally increased from about 0.7 - 0.8 at the start of saturation to 0.95 - 0.97 at the end. The saturation phase usually took about twenty hours.

86. After saturation, the specimen was ready for the consolidation phase of the test. With the drain valve closed, the cell pressure was raised such that the difference between it and the backpressure was the initial effective confining stress. The burette reading and system resonant frequency were recorded. At the same time the drainage line was opened and a timer was started. Readings of the burette and the system resonant frequency were taken at predetermined elapsed times. The burette readings were plotted against the log-of-time and the square root of time. The time for 100% primary consolidation, t_{100}, differed somewhat between the two methods. The log-time procedure generally gave larger values by a factor of about 1.4-1.5 over the square root of time method. In addition, G_{max} was plotted against the log-of-time. This curve became linear once secondary compression was reached. The

consolidation phase was considered complete when the curve of G_{max} vs. the log-of-time was tangent for one log-cycle of time. The time for this portion of the test was about twenty hours.

87. The rate of deformation was an important consideration. In order to get a true representation of the effective stress path, it was desired to have pore-pressure equalization throughout the specimen fairly early in the test. For the undrained tests, the rate of axial strain was found by using the procedure outlined by BISHOP AND HENKEL 1962. Using a conservative t_{100} of 70 minutes, the rate of deformation was found to be 0.0064 mm/min (0.000253 in/min). This would allow for 95% pore pressure equalization at 1% axial strain. The actual rate used was 0.0056 mm/min (0.00022 in/min). To insure adequate pore pressure dissipation in the drained tests, procedures recommended by BISHOP AND HENKEL 1962 were also used. The required rate of axial deformation was 0.002 mm/min (0.00008 in/min). The actual rate of testing for the drained tests was 0.0023 mm/min (0.00009 in/min) or about one-third the rate for the undrained tests.

88. The loading phase was continued until failure occurred. Failure was defined as the point of maximum obliquity, i.e., maximum ratio of major effective principal stress to minor effective principal stress. In several tests maximum obliquity was not well defined. For these cases the axial loading was halted after the stress path had become sufficiently tangent to the K_f line. Generally the time of axial load application for an undrained test was about 20 hours and 60 hours for a drained test.

89. The test takedown phase was a reverse of the setup procedure. After the apparatus was disassembled a final moisture content sample was

taken from the specimen. The excess oil was cleaned from the apparatus components, and the test area was prepared for the next test.

Results of Resonant Column/Triaxial Compression Tests

90. The soil tested was identically the same as the remolded soil used in the torsional simple shear tests and the soil is described in Appendix C. The primary objectives of these tests were to demonstrate the use of this type of test (whether drained or undrained) for establishing normalized shear stress-shear strain behavior and to show that the normalized stress-strain behavior was relatively independent of effective stress path.

91. The three undrained tests will be described first. Effective stress paths for these tests are given in Fig. 45. All three become tangent to a K_f-line that corresponds to an angle of shearing resistance of 36 degrees. The tests with the higher confining stresses exhibit greater relative amounts of positive excess pore pressure, i.e., larger values of the "A" pore pressure coefficient.

92. The axial stress versus axial strain data for the undrained tests are given in Figs. 46 through 48. These results are quite typical of conventional undrained triaxial tests.

93. These data were converted to shear stress versus shear strain and then normalized by use of τ_{max} and reference strain using the procedures given in Part II of this report. The normalized curves are presented in Fig. 49 where it can be seen that, for practical purposes, a single curve exists.

94. For the four drained tests, the effective stress paths are given

in Fig. 50. The test with effective confining stress of 100 kPa (14.5 psi) was stopped before failure because of a time constraint. Had it continued, it would have been consistent with the other tests. The K_f-line for these tests corresponds to an angle of shearing resistance of 36 degrees which is identical to the angle obtained for the undrained tests.

95. The axial stress versus axial strain data for these four tests are given in Figs. 51 through 54. In each of these tests, a concerted effort was made to obtain data at small axial strains. In each of the curves, there appears to be a "yield" point at very low axial strains (< 0.05 percent). Since these tests were performed at a strain rate approximately one-third that of the undrained tests, it is believed that the "yield" point is the stress level at which creep effects begin to become significant. Beyond this point, the axial stress versus axial strain curves are much flatter than corresponding curves in the undrained tests. (For example, compare the drained curve in Fig. 51 with the undrained curve in Fig. 47. Both exhibit approximately the same shear strength but stress-strain behavior is significantly different.)

96. Next, the drained axial stress-axial strain data were converted to shear stress-shear strain and then they were normalized by use of τ_{max} and reference strain. The normalized curves are given in Fig. 55. For practical purposes, a single curve could represent the data.

97. If the normalized curves for the drained tests (Fig. 55) are compared with those for the undrained tests (Fig. 49), near perfect agreement is achieved for normalized strains less than 0.2 and there is agreement again for normalized strains greater than 150. In between there is a departure of the two with the drained curves being below the

undrained curves by a maximum of about 15 percent. It is unclear at the present time whether this difference is due to creep effects (the drained tests were run at one-third the rate of the undrained ones) or due to a shortcoming in the theory. This could be answered by performing several undrained tests at the slower rate. It should be pointed out that the normalized curves are in much closer agreement than the drained and undrained axial stress-axial strain curves for tests giving the same shear strength. For those, axial stress for a given axial strain may differ by 50 percent. If the difference in the normalized curves is found to be caused by creep, then their use would be an excellent way to describe creep behavior on a systematic basis.

98. One side benefit of performing these tests was to obtain measured values of initial tangent shear modulus for each stress point along the stress paths. In the theory presented in Part II of this report, only the value of initial tangent shear modulus prior to the start of axial loading is required. For subsequent points, the value of initial tangent shear modulus was adjusted by considering changes in mean effective confining stress and for the drained tests, changes in void ratio as well. Comparison of measured versus predicted values of initial tangent shear moduli for these tests shows agreement that is usually within ten percent. Better agreement could be achieved by refining the adjustment equation but, at least for the present, such refinement is not warranted.

99. Finally, in Fig. 56, the normalized data from both the torsional simple shear tests and the triaxial/resonant column tests are compared. It can be seen that the torsional simple shear data and the undrained triaxial/resonant column data agree very well and a single

curve can be used to describe this normalized behavior. The drained triaxial/resonant column data lie somewhat below the first curve but still the difference is within acceptable limits.

PART IV: DISCUSSION AND APPLICATION

General

100. The test data presented in the previous part of this report has shown that for normally consolidated soils, the use of τ_{max} and reference strain to normalize stress-strain data provides a normalized curve which is independent of effective stress path and sample disturbance. Hence, the normalized stress-strain curve should apply to insitu conditions as well. The next logical step is to apply the inverse of the normalization process to establish stress-strain behavior insitu.

101. To obtain stress-strain behavior from normalized stress-strain behavior, two items are needed: τ_{max} and reference strain. For insitu stress-strain behavior, values of τ_{max} and reference strain that reflect field conditions must be established. Fortunately, this can be done with reasonable accuracy by use of existing techniques of laboratory and field testing. The procedure employed varies somewhat depending on whether loading conditions in the field occur slowly enough such that drained conditions may be assumed to exist or whether undrained conditions must be assumed. Each will be handled separately.

102. Both methods require an estimate of the initial state of effective stress insitu. In the case of horizontal ground surface, this means determining the vertical effective stress and the horizontal effective stress or the coefficient of lateral earth pressure at rest, K_o. The vertical effective stress can usually be estimated with reasonable accuracy. Lateral effective stresses are more difficult to establish. If insitu measurement of these is prohibitive, then they may

be estimated by use of the coefficient of earth pressure of rest, K_o. Values of K_o can be obtained from BROOKER AND IRELAND 1965

$$K_o = 0.95 - \sin \phi' \tag{18}$$

where ϕ' = effective angle of shearing resistance

or from ALPAN 1976

$$K_o = 0.19 + 0.233 \log (PI \%) \tag{19}$$

where PI = plasticity index in percent

103. Determination of stress-strain behavior insitu also requires that the initial tangent shear modulus, G_{max}, be known. There is a variety of techniques currently available to do this with good accuracy. The recent review by WOODS 1978 discusses these in detail. The cross-hole seismic method appears to be the most accurate and is to be preferred. In certain cases, the Hardin Equation (see Eq. 3) may provide sufficiently accurate estimates of G_{max} insitu but values obtained by measurement are strongly recommended.

Insitu Stress-Strain Behavior for Drained Conditions

104. It has been shown by SKEMPTON AND SOWA 1963, BROMS 1978, and others that for normally consolidated soils, the shear strength parameters in terms of effective stress, c' and ϕ', are quite accurately

determined for insitu conditions by means of laboratory tests performed on relatively undisturbed specimens. It is recommended that laboratory determined values be used in this procedure.

105. Next, the effective stress path insitu must be estimated. For drained conditions, where no excess pore pressures occur, the stress path for a given loading can be estimated assuming elastic behavior. (Although soil behavior is not elastic, many of the elastic solutions are independent of elastic parameters or have only a minor dependency on Poisson's ratio.) Charts presented by PERILOFF AND BARON 1978 may be especially helpful in this.

106. The effective stress paths for which this process is applicable are ones that are predominately shear in nature and would correspond to the "Class 1 Loadings" described by HARDIN 1978. See Fig. 57 for the range of these stress paths. Note that the stress paths emanate from the stress point that corresponds to the state of effective stress insitu. If the entire effective stress path is not vertical, values of T_{max} and G_{max} will change for each point along the stress path. Sufficiently accurate results are obtained for these situations if the stress path is described by ten to twenty points. The insitu stress-strain curve will be established by summing the shear strain increments associated with stress path increments from one stress point to the next.

107. For each stress point, j, the value of $(T_{max})_j$ is calculated

from

$$(\tau_{max})_j = [(q_f)^2_j - q^2_i]^{0.5} \quad (20)$$

where $(q_f)_j = c' \cos \phi' + p'_j \sin \phi'$

$p'_j = 0.5[(\sigma'_1)_j + (\sigma'_3)_j]$

$q_i = 0.5[(\sigma'_1)_i - (\sigma'_3)_i]$

= ordinate of stress point before loading began

The applied shear stress at each stress point, τ_j is determined from

$$\tau_j = [q^2_j - q^2_i]^{0.5} \quad (21)$$

For each stress path increment, j, the incremental normalized shear strain, $\Delta(\gamma/\gamma_r)_j$ can be established by entering the normalized stress-strain curve determined from laboratory tests with values of $\tau_j/(\tau_{max})_j$ and $\tau_{j-1}/(\tau_{max})_{j-1}$ and obtaining values of $(\gamma/\gamma_r)_j$ and $(\gamma/\gamma_r)_{j-1}$. The incremental normalized shear strain is given by

$$\Delta(\gamma/\gamma_r)_j = (\gamma/\gamma_r)_j - (\gamma/\gamma_r)_{j-1} \quad (22)$$

This value must be multiplied by a value of reference strain associated with that stress path increment to obtain an incremental shear strain. Reference strain, from Eq. (1) requires values of τ_{max} and G_{max}. The value of τ_{max} for the increment can be obtained by averaging the values for the stress points that define the increment.

$$[\tau_{max}]_{incr.\ j} = 0.5[(\tau_{max})_j + (\tau_{max})_{j-1}] \qquad (23)$$

where $(\tau_{max})_j$ and $(\tau_{max})_{j-1}$ are obtained from Eq. (20).

108. The value of G_{max} associated with the stress path increment can be estimated from the value obtained from seismic measurements insitu adjusted for the change in mean effective confining stress changes associated with the middle of the stress path increment as given by

$$(\sigma'_o)_j = 1/3[(\sigma'_1)_j + (\sigma'_2)_j + (\sigma'_3)_j] \qquad (24)$$

For plane strain loading conditions, this may be defined in terms of the stress point coordinate

$$(\sigma'_o)_j = 0.5[p'_j + p'_{j-1}] \qquad (25)$$

For axis-symmetrical compression conditions, it can be described by

$$(\sigma'_o)_j = 0.5[(p'_j - 2q_j/3) + (p'_{j-1} - 2q_{j-1}/3)] \qquad (26)$$

and for axis-symmetrical extension conditions by

$$(\sigma'_o)_j = 0.5[(p'_j + 2q_j/3) + (p'_{j-1} + 2q_{j-1}/3)] \qquad (27)$$

The value of G_{max} for the stress increment is given by

$$[G_{max}]_{incr.\ j} = [G_{max}]_{seismic} \times \left[\frac{(\sigma'_o)_j}{(\sigma'_o)_i}\right]^{0.5} \qquad (28)$$

where $(\sigma'_o)_i$ = the mean effective confining stress for insitu conditions before load application

The value of reference strain for each stress path increment is given by

$$[\gamma_r]_{incr.\ j} = \frac{[\tau_{max}]_{incr.\ j}}{[G_{max}]_{incr.\ j}} \qquad (29)$$

The shear strain increment is calculated from

$$\Delta\gamma_j = \Delta(\gamma/\gamma_r)_j * [\gamma_r]_{incr.\ j} \qquad (30)$$

The shear strain for each stress point is calculated from

$$\gamma_j = \gamma_{j-1} + \Delta\gamma_j \qquad (31)$$

where γ_{j-1} = the total shear strain to the stress point "j-1". A value of zero is assigned to γ_{j-1} for the stress point corresponding to initial insitu conditions (before loading begins). A plot of τ from Eq. (21) versus γ from Eq. (31) will give the stress-strain curve for the given loading.

Insitu Stress-Strain Behavior for Undrained Conditions

109. Undrained conditions differ from the previously discussed drained conditions in that the effective stress path cannot be estimated by use of elasticity because of the excess pore pressures created by soil attempting to dilate. In fact, it is recognized that the effective stress path is quite independent of total stress path for saturated undrained conditions (see LAMBE AND WHITMAN 1969, p. 400). Consequently, the shear stress-shear strain should also be independent of total stress path. For this situation, the problem reduces to 1) determining the effective stress path insitu and 2) determining the shear stress-shear strain behavior for that effective stress path.

110. One additional piece of information is required from insitu tests for this case; the undrained shear strength, S_u. This may be determined by any method that provides acceptable results. Methods such as vane shear, pressuremeter, cone penetrometer, borehole shear, etc., may be used according to the soil type, local experience, and preference. For a given soil, it is common to express the undrained shear strength in terms of S_u/σ'_v where σ'_v is the effective overburden stress. Typical values of S_u/σ'_v are given by LAMBE AND WHITMAN 1969, p. 452.

111. With this information and information on the state of stress insitu and the shear strength parameters c' and ϕ' from laboratory tests, sufficient information is available to establish the starting and ending stress points on the insitu effective stress path. The starting point is simply established from the initial state of stress insitu (see Fig. 58). The ending point is determined by the intersection of the K_f - line (line on stress-path diagram associated with Mohr Coulomb effective

stress failure envelope) and the insitu undrained shear strength (see Fig. 58).

112. There are a number of ways to estimate the stress path between the starting and ending points. The simplest is to use a straight line (long-dashed stress path in Fig. 58). Although the actual effective stress path is likely to be curved (short – dashed stress path in Fig. 58), the associated shear stress-shear strain behavior may not be significantly affected.

113. The more rational way to estimate the effective stress path is to fit the starting and ending points with a curve which is derived from the effective stress path measured in the laboratory when the undrained test was used to establish the normalized stress-strain behavior. The effective stress path from the undrained laboratory test may be described as shown in Fig. 59a where the parameter H is defined as the inverse of the slope of the secant connecting the initial stress point and any other stress point (see Fig. 59b). The value of H may be calculated from

$$H = -(p' - p_i')/(q - q_i) \qquad (32)$$

114. The value of H associated with the intersection of the stress path and the K_f line (failure) is defined as H_f. For insitu conditions, the value of H_f is defined because the starting and ending points of the stress path are defined (see Fig. 58). The value of H_f is also uniquely determined by S_u/σ'_v and ϕ' with the equation

$$H_f = 1/(S_u/\sigma'_v) - 1/(\sin \phi') \qquad (33)$$

To obtain the intermediate stress points, choose values of T/T_{max} between zero and unity from the laboratory generated curve of H/H_f versus T/T_{max}. The value of H_{insitu} corresponding to T/T_{max} is given by

$$H_{insitu} = (H/H_f)_{lab} \times (H_f)_{insitu} \tag{34}$$

The ordinate of the stress point insitu is given by

$$q = p'_i \frac{-T^2 a_1 a_3 + \sqrt{T^4 a^2_1 q^2_i - T^2 (a^2_1 q^2_i + q^2_i - a^2_2) + q^2_i}}{(1 - T^2 a^2_1)} \tag{35}$$

where: $a_1 = -(H)\sin \phi'$

$a_2 = (c')\cos \phi' - (p_i' + H\, q_i)\sin \phi'$

$T = T/T_{max}$

The abscissa of the stress point is given by

$$p' = p_i' - H(q - q_i) \tag{36}$$

and the coordinates of the stress point are established. From this point, the procedure for establishing the insitu shear stress-shear strain behavior is identical to that for drained conditions.

PART V: CONCLUSIONS AND RECOMMENDATIONS

115. A new approach has been outlined for handling the problem of sample disturbance. The technique makes use of laboratory tests to describe the "sense" of the stress- strain behavior and requires field measured results to establish the "magnitude" of the behavior. This process is analogous to classical plasticity which utilizes a plastic potential function to establish the direction of a plastic strain increment and hardening function to establish the magnitude of the increment. The normalized stress-strain curve determined in the laboratory is analogous to the plastic potential function and the field determined data are analogous to the work hardening law.

116. The procedures were developed for establishing the normalized stress-strain behavior by use of drained or undrained laboratory tests. Either a torsional simple shear test or a combination of resonant column and triaxial tests may be used. The procedures are consistent with each other and with normalization procedures previously published by the Principal Investigator and his colleagues.

117. Results of resonant column and torsional simple shear tests on normally consolidated cohesive soils were presented and compared. It was shown that a disturbance to the soil by applying as much as 2 percent shear strain did not significantly affect the normalized shear stress-shear strain but significantly affected the initial tangent shear modulus and undrained effective stress path. It can be concluded from this that the normalized stress-strain curve would also apply to insitu conditions as well.

118. The topic of anisotropic states of stress has been fully

incorporated in this work and it should be possible to predict behavior of soil from anisotropic state of stress based on laboratory test results performed on isotropically consolidated specimens. Additional testing is in order to verify this. The topic of anisotropic structure has not been addressed except that if the direction of shear application in the laboratory is the same as that insitu, then the method is independent of structural anisotropy.

119. The normalized stress-strain curve appears to be relatively independent of effective stress path. To verify this, special torsional simple shear tests and triaxial resonant column tests were performed on specially remolded specimens. The normalized results from both types of tests agreed well with each other. Furthermore, the normalized behavior appears to be sensitive to creep. It is recommended that this normalization process be used to study creep on a systematic basis. Some additional study is needed on this topic.

120. The process of establishing the shear stress-shear strain behavior insitu is essentially the inverse of the process used in the laboratory to obtain the normalized behavior. Procedures for both drained conditions and undrained conditions insitu are detailed. The former only requires the initial tangent shear modulus from field testing, whereas the latter requires both the initial tangent shear modulus and the undrained shear strength. The procedures are based on accepted principles of soil mechanics and as a result should give acceptable results. Evaluation of the technique by use in actual cases is in order.

121. Finally, the processes worked out herein are only applicable to normally or near normally consolidated soils. With modification,

these processes should be applicable to overconsolidated soils. Further work on this is strongly recommended.

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TABLE 1. VALUES OF COEFFICIENT K FOR HARDIN EQUATION

PLASTICITY INDEX	K
0	0
20	0.18
40	0.30
60	0.41
80	0.48
>=100	0.50

TABLE 2. DESCRIPTION OF SOILS USED IN RESONANT COLUMN AND TORSIONAL SIMPLE SHEAR TESTS

SOIL NO.	TEST IDENT.	SOIL DESCRIPTION	UNIFIED CLASS.	WC (%)	VOID RATIO	LL (%)	PL (%)	SP. GR.	SENS. **	SH. STR. (KPA)	SATUR. (%)	DEN. (KG/M*3)
1	KYD1A (KYD1)*	KENTUCKY CLAY FROM DAVIESS COUNTY, GRAY IN COLOR. DEPTH 10M	ML-CL	28.1	0.76	35	23	2.72	--	65.8	99.12	1968.0
2	JW3260 (SKA)*	SKA EDEBY POSTGLA-CIAL CLAY FROM SWEDEN. LIGHT COLORED STRATIFIED CLAY. DEPTH 4M	CH	93.0	2.59	70	25	2.79	10	6.16	100.0	1498.5
3	SKA	SAME AS ABOVE	CH	72.5	2.59	70	25	2.79	10	6.16	100.0	1616.5
4	S-19 (MAC)*	MISSISSIPPI CANYON AREA CLAY. 7M BELOW SEAFLOOR.	MH	90.7	2.41	108	34	2.66	2	5.95	100.0	1485.9
5	DRAM	DRAMMEN CLAY FROM SUNDLAND NORWAY. DEPTH 7M	CL	47.4	1.16	59	32	2.45	14	27.9	100.0	1671.9
6	JW5337 (VAL)*	VALEN CLAY FROM GOTHENBERG SWEDEN 5%-6% ORGANIC CONTENT. DEPTH 5M	CH	111.9	2.8	104	37	2.5	9	15.2	100.0	1411.9
7	JW6825	BACKEBOL CLAY, NORTH GOTHENBERG. SOFT NORMALLY CONSOLIDATED CLAY AND HOMOGENEOUS. DEPTH 7M	MH	74.3	1.75	60	32	2.65	7	14.9	100.0	1678.1
8	JW6825B	SAME AS ABOVE	MH	60.2	1.61	60	25	2.68	7	27.9	100.0	1643.2
9	SA-7	PACIFIC CLAY FROM CALIFORNIA. GRAY COLOR WITH SAND AND SHELL LAYERS. DEPTH 7M	CL	35.8	1.026	37	22	2.75	--	40.0	96.0	1840.0
10	6249 (SGI1)*	NORRKOPING CLAY SWEDEN. DEPTH 7M	CH	70.8	1.49	58	21	2.28	10	17.5	100.0	1565.5

* TORSIONAL SIMPLE SHEAR TEST DESIGNATION, ** BY SWEDISH FALL CONE

TABLE 3. DATA OF "UNDISTURBED" SOILS TESTED IN TORSIONAL SIMPLE SHEAR

(SEE TABLE 2. FOR FOR SOIL PROPERTIES)			MEAN EFFECTIVE CONFINING STRESS (KPA)				INITIAL TANGENT SHEAR MODULUS, G(MAX) (MPA)					
SOIL NAME	TEST IDENT.	ϕ'	BEFORE LARGE AMPL. TESTING		AFTER LARGE AMPL. TESTING		END OF PRIMARY CONSOL.		BEFORE LARGE AMPL. TESTING		AFTER LARGE AMPL. TESTING	
		DEG.	TEST 1	TEST 2	TEST 1	TEST 2	TEST 1	TEST 2	TEST 1	TEST 2	TEST 1	TEST 2
KY. CLAY FROM DAVIESS CO., KY.	KYD1	35	263.7	262.8	156.9	170.2	56.7	58.9	73.5	72.0	45.3	61.2
NORRKOPING CLAY, SWEDEN	SGI1	27	77.5	-	76.8	-	-	-	12.1	-	7.7	-
VALEN CLAY FROM GOTHENBERG, SWEDEN	VAL1	23	61.4	66.2	46.3	47.0	6.1	-	10.8	7.1	-	4.5
BACKEBOL CLAY	JW	29	40.6	38.0	33.9	30.1	5.5	6.3	8.5	6.4	5.2	5.2
DRAMMEN CLAY FROM NORWAY	DRAM	29	63.7	58.6	28.7	36.9	16.7	25.6	19.1	25.6	8.6	10.7
MISSISSIPPI CANYON CLAY GULF OF MEXICO	MAC	22	72.8	71.8	48.4	62.1	7.2	6.9	10.1	8.5	6.1	6.9
SKA EDEBY CLAY FROM SWEDEN	SKA	26	40.9	37.8	18.0	17.6	8.3	7.4	7.2	8.3	4.9	5.2
KY. CLAY FROM DAVIESS CO., KY.	KJK2	35	93.0	-	60.5	-	13.9	-	18.9	-	10.6	-

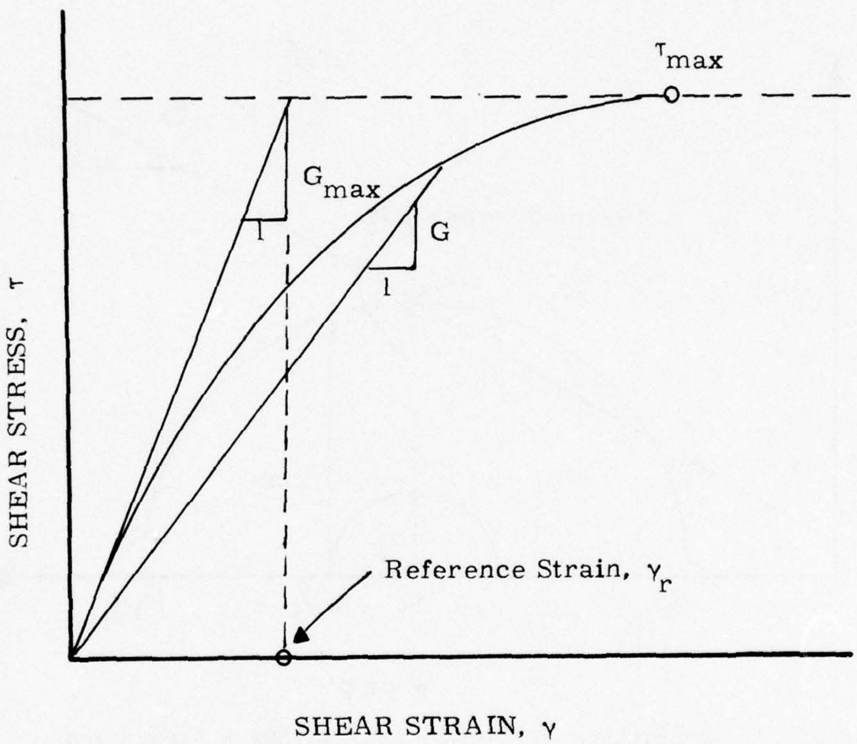


Fig. 1. The Concept of Reference Strain

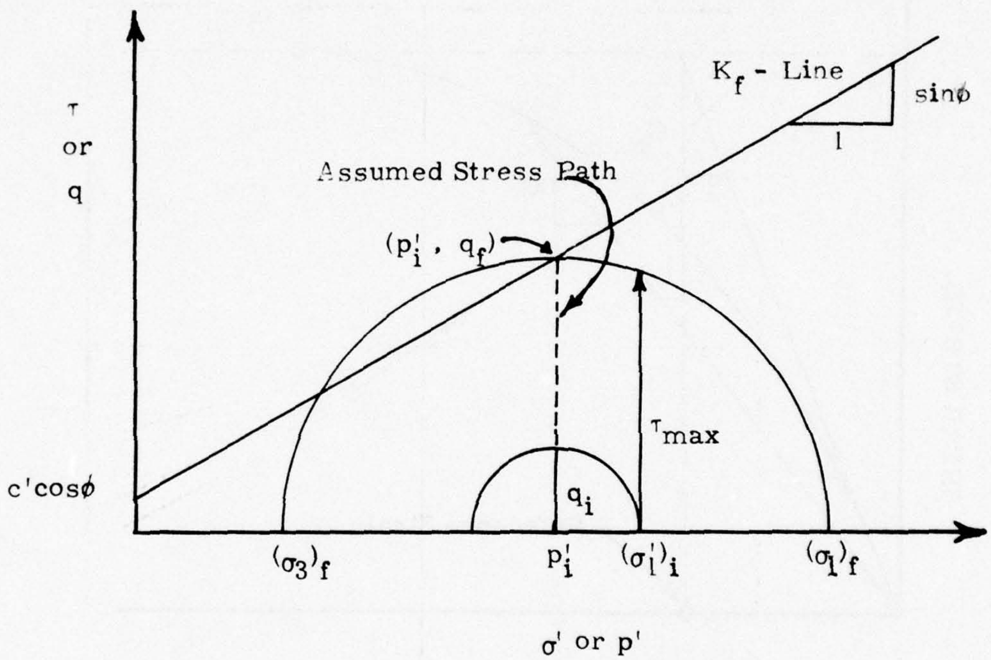


Fig. 2. Definition of Maximum Applied Shear Stress and Stress Path for Drained Pure Shear Loading

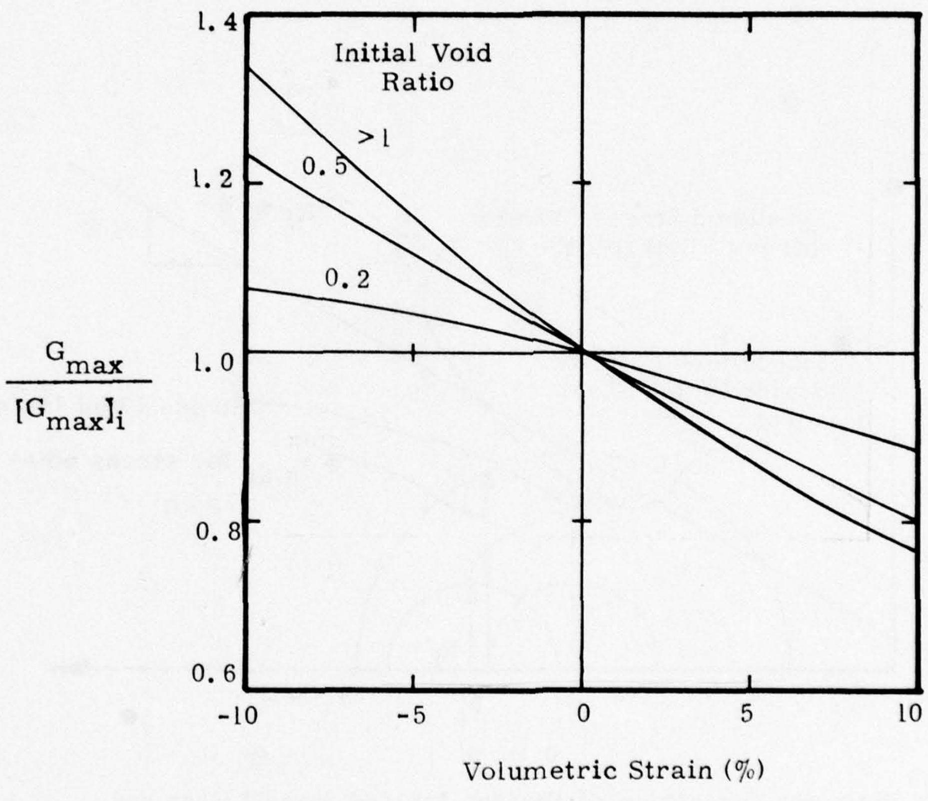


Fig. 3. Effect of Volumetric Strain on G_{max}

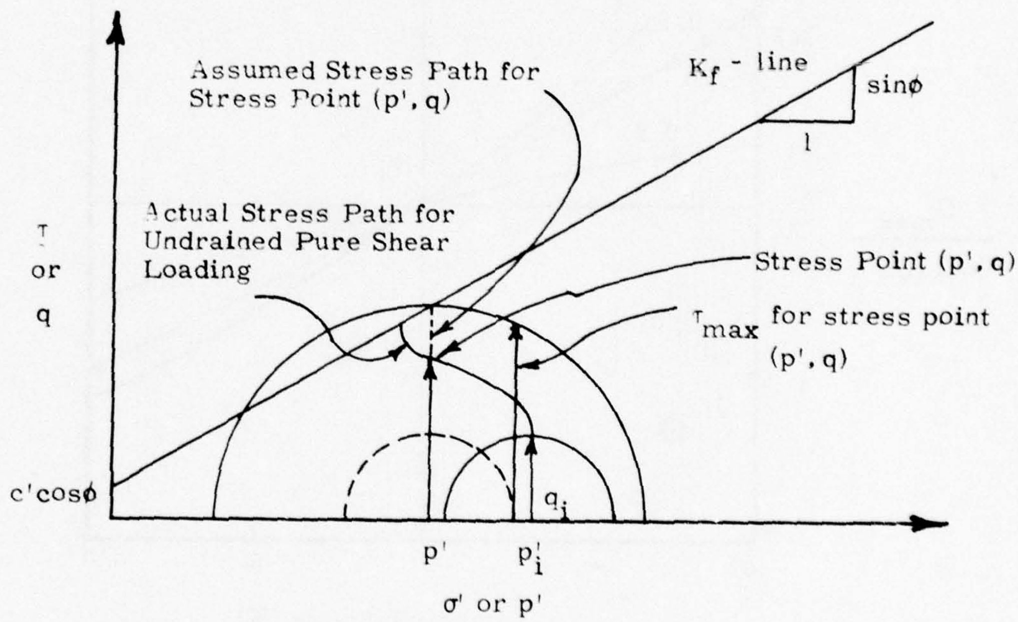


Fig. 4. Definition of Maximum Applied Shear Stress and Stress Path for Undrained Pure Shear Loading

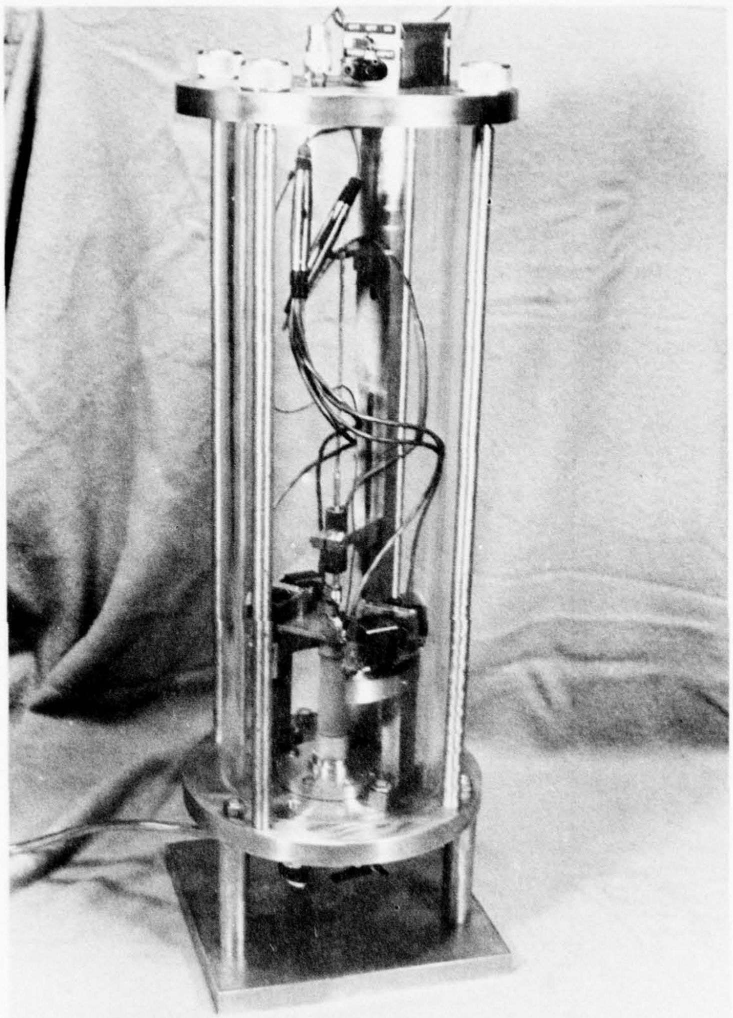


Fig. 5. Drnevich Torsional Resonant Column Apparatus

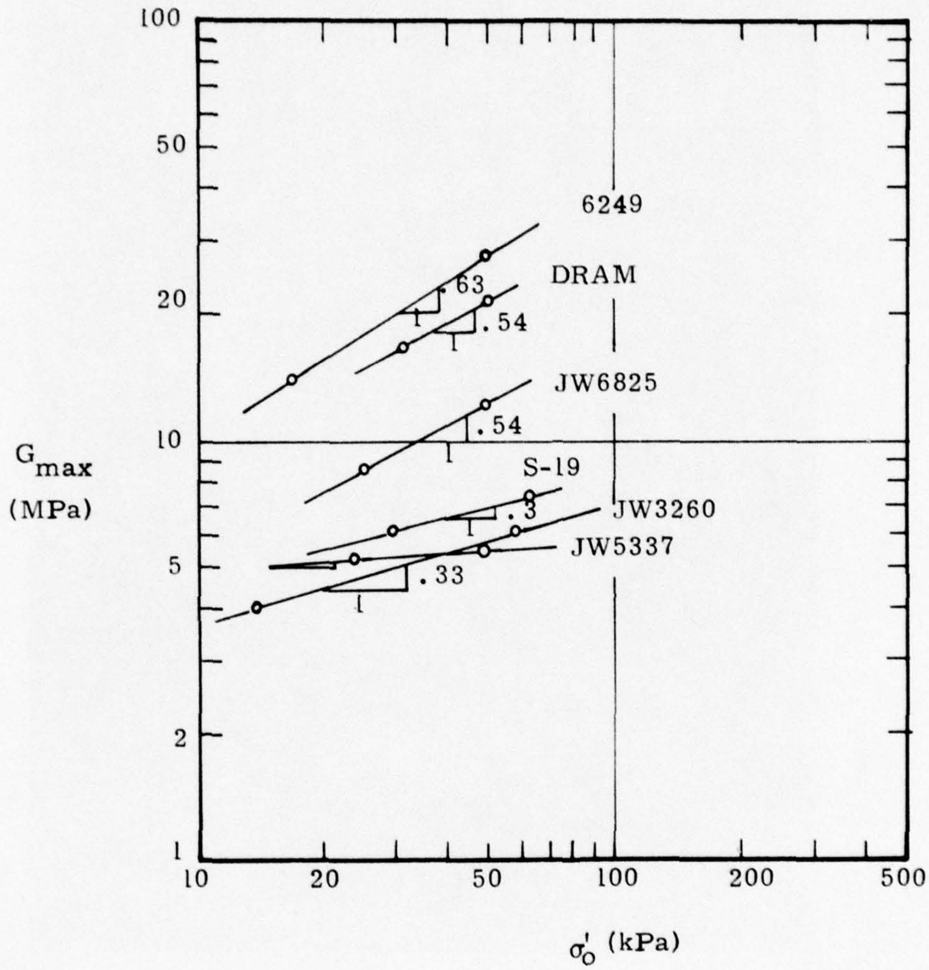


Fig. 6. Initial Tangent Shear Modulus at End of Primary Consolidation from Resonant Column Tests

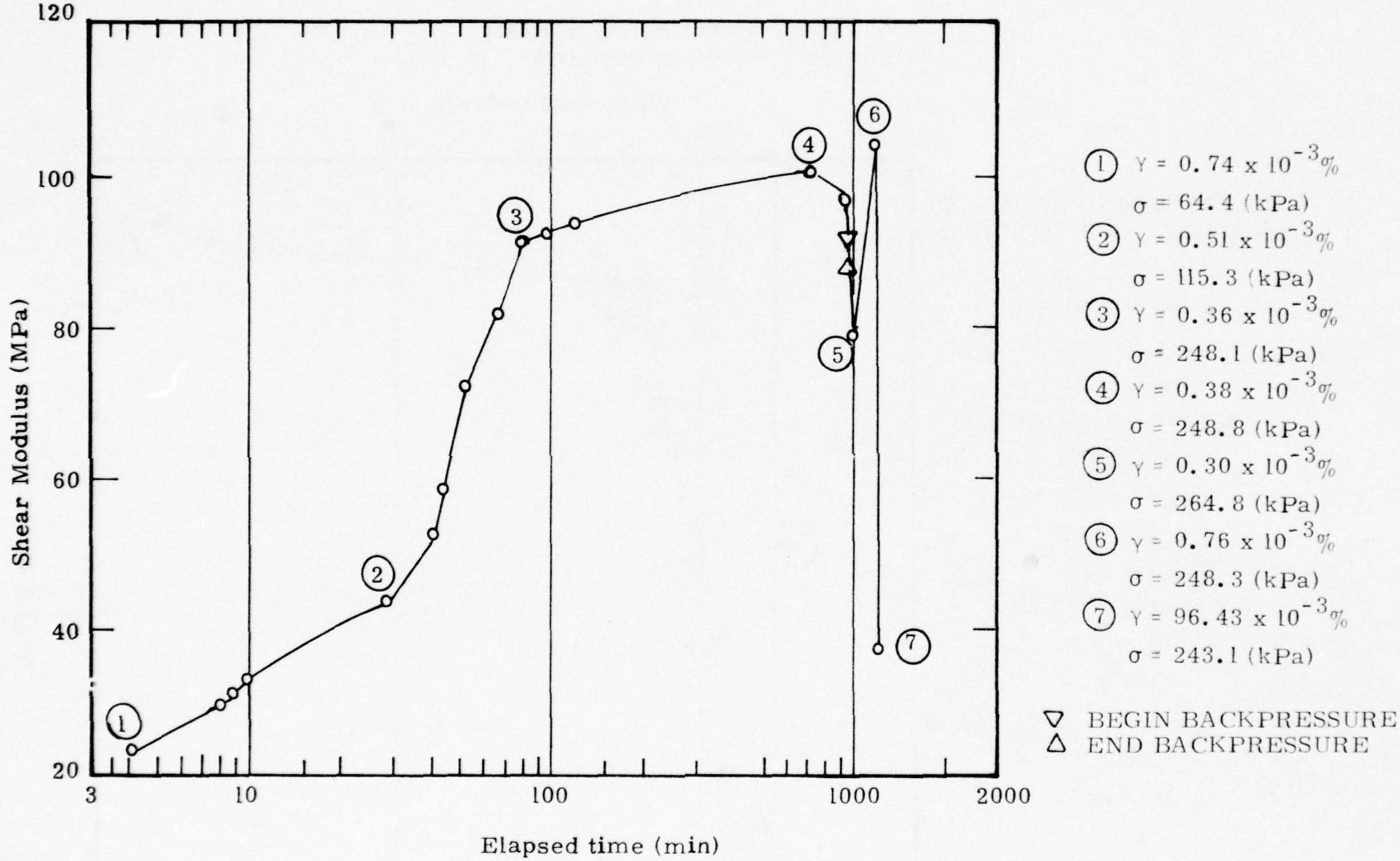


Fig. 7. Shear Modulus versus Elapsed Time
Resonant Column Sample KYD1A

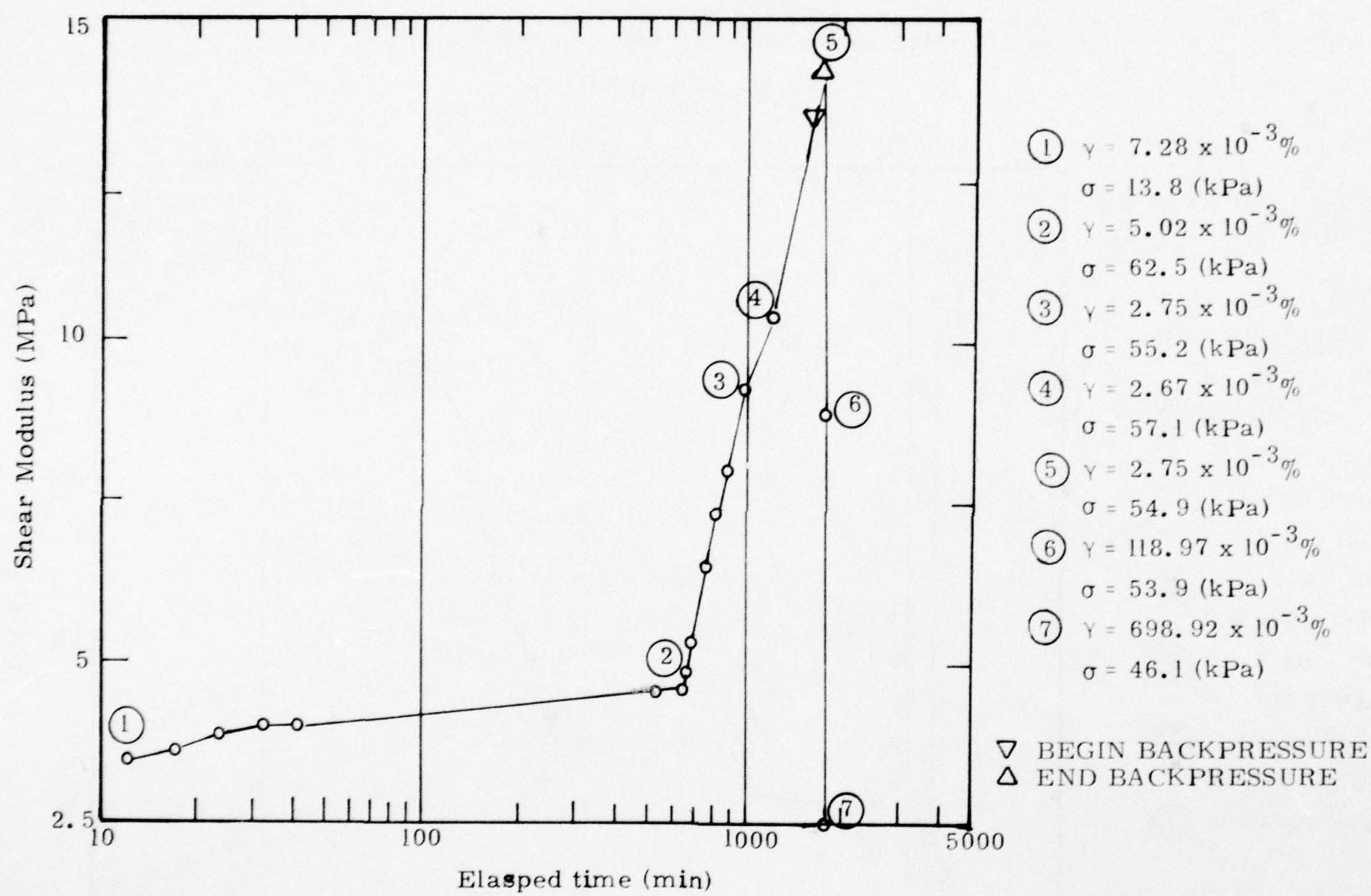


Fig. 8. Shear Modulus versus Elapsed Time
Resonant Column Sample JW3260

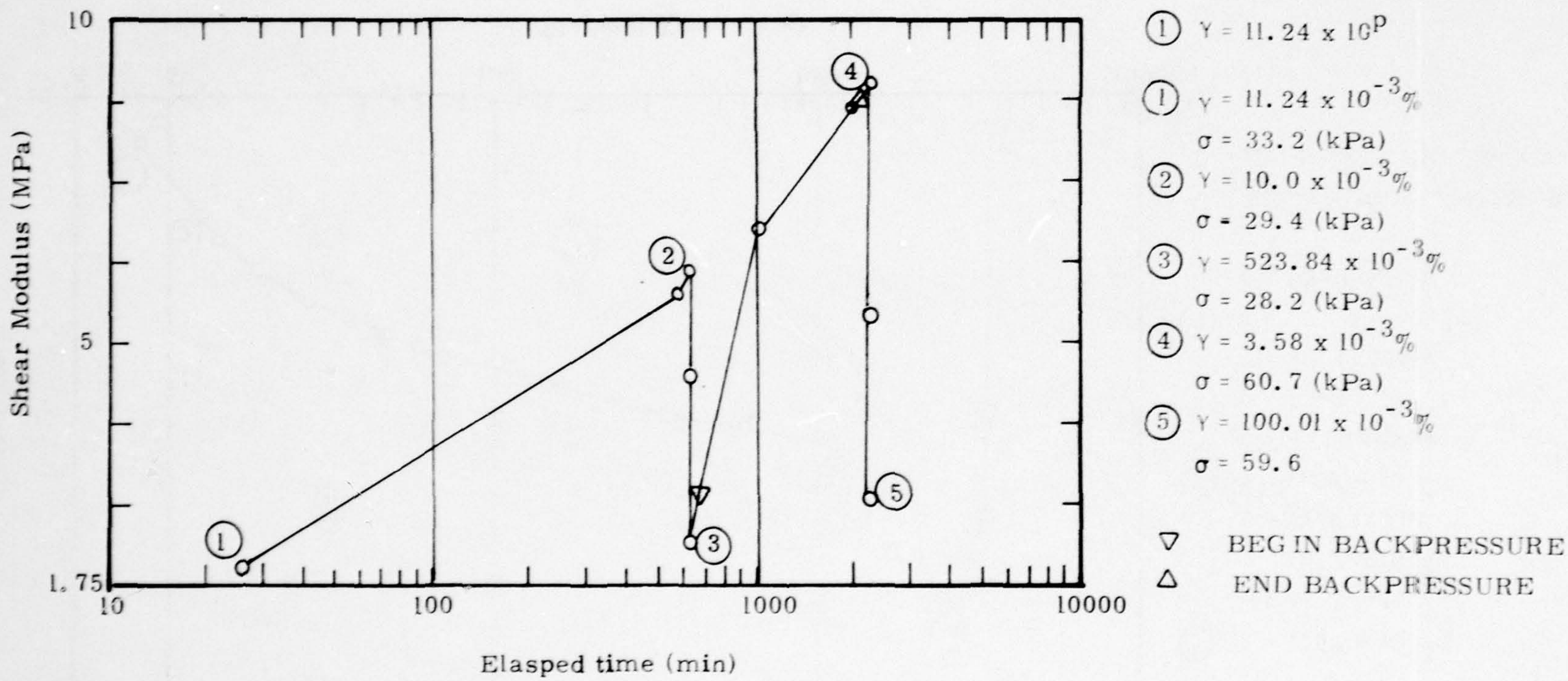


Fig. 9. Shear Modulus versus Elapsed Time
Resonant Column Sample S-19

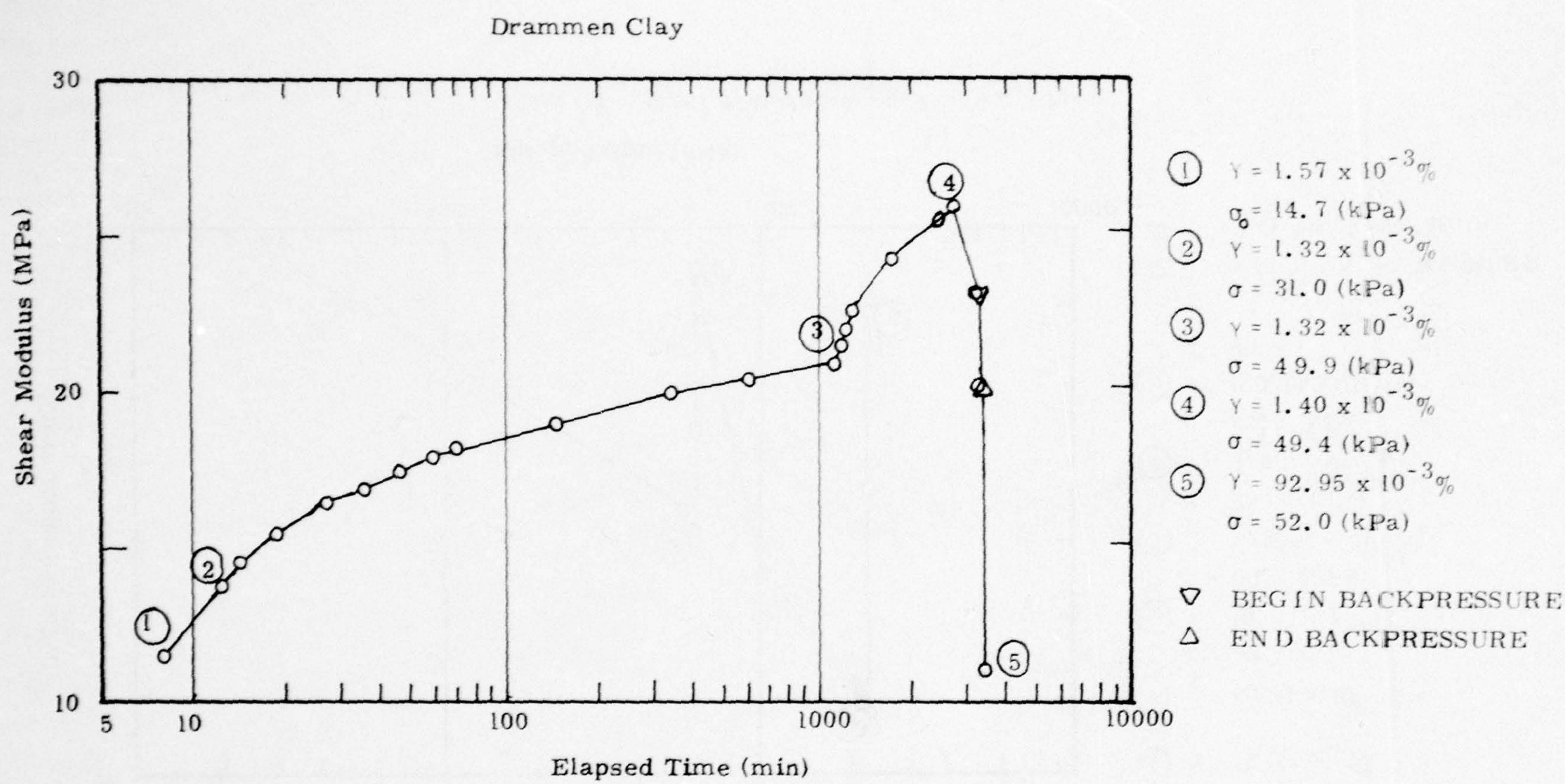
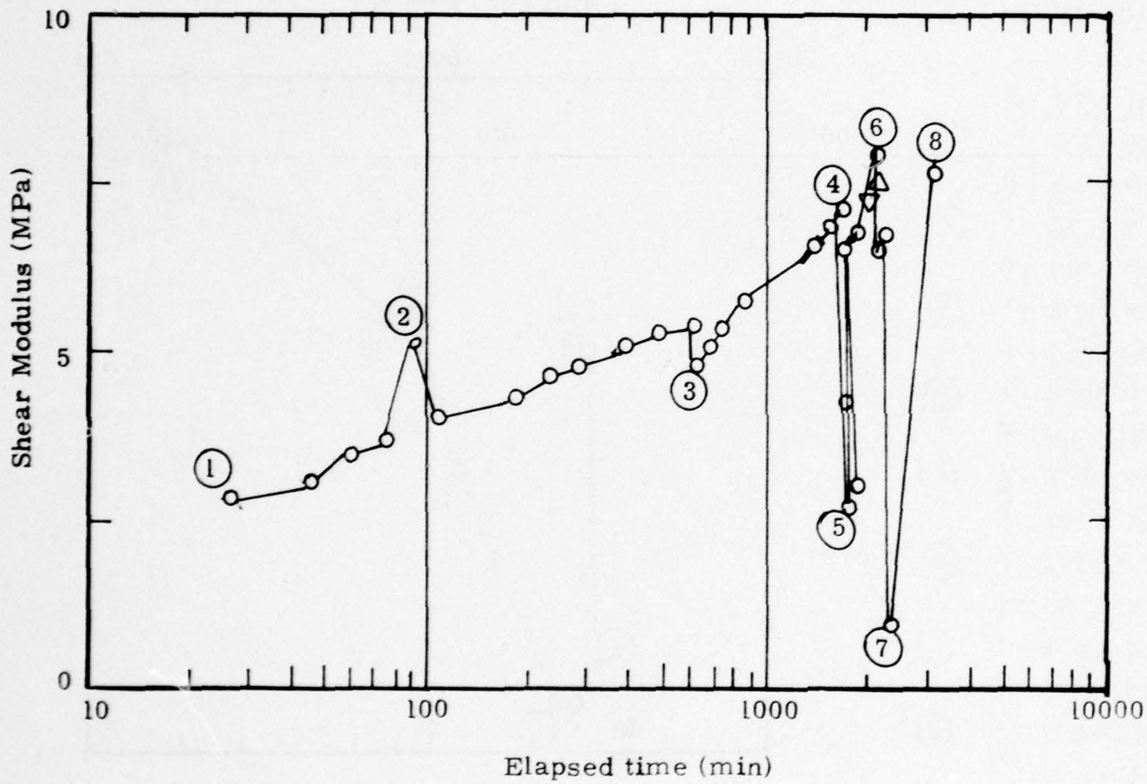


Fig. 10. Shear Modulus versus Elapsed Time Resonant Column Sample A-1 (Drammen)



① $\gamma = 3.05 \times 10^{-3}\%$

$\sigma_o = 26.6$ (kPa)

② $\gamma = 3.87 \times 10^{-3}\%$

$\sigma = 23.8$ (kPa)

③ $\gamma = 4.74 \times 10^{-3}\%$

$\sigma = 50.0$ (kPa)

④ $\gamma = 4.18 \times 10^{-3}\%$

$\sigma = 47.9$ (kPa)

⑤ $\gamma = 472.5 \times 10^{-3}\%$

$\sigma = 45.7$ (kPa)

⑥ $\gamma = 3.89 \times 10^{-3}\%$

$\sigma = 46.6$ (kPa)

⑦ $\gamma = 202.2 \times 10^{-3}\%$

$\sigma = 44.1$ (kPa)

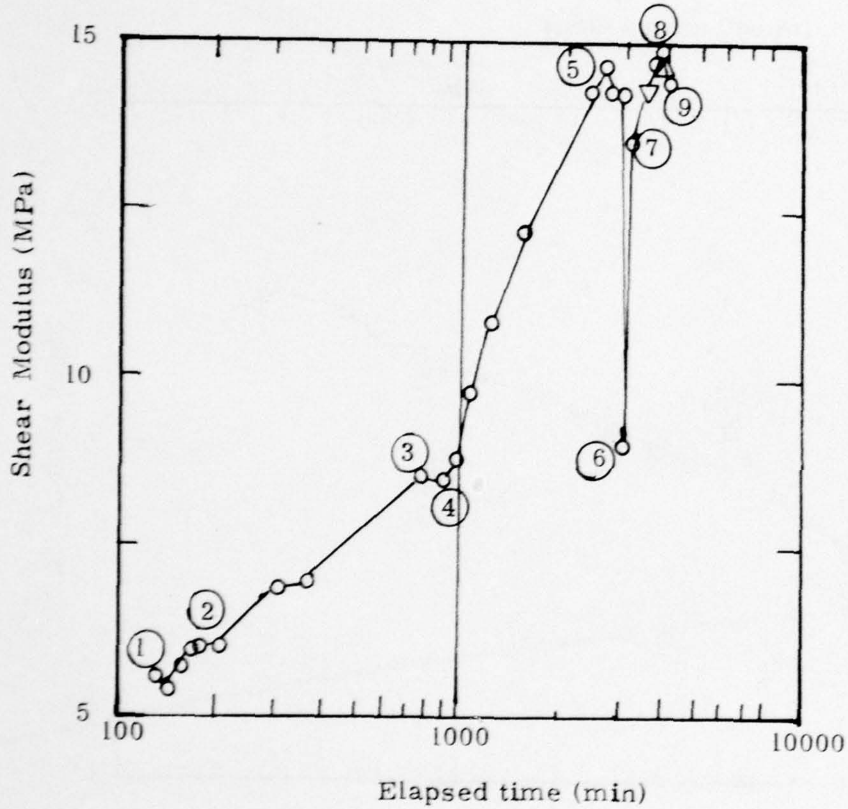
⑧ $\gamma = 3.88 \times 10^{-3}\%$

$\sigma = 48.0$ (kPa)

▽ BEGIN BACKPRESSURE

△ END BACKPRESSURE

Fig. 11. Shear Modulus versus Elapsed Time
Resonant Column Sample JW5337 (Valen)



① $\gamma = 8.0 \times 10^{-3}\%$

$\sigma_o = 6.9$ (kPa)

② $\gamma = 5.0 \times 10^{-3}\%$

$\sigma = 24.9$ (kPa)

③ $\gamma = 3.0 \times 10^{-3}\%$

$\sigma = 26.2$ (kPa)

④ $\gamma = 2.74 \times 10^{-3}\%$

$\sigma = 49.3$ (kPa)

⑤ $\gamma = 2.48 \times 10^{-3}\%$

$\sigma = 49.7$ (kPa)

⑥ $\gamma = 2.06 \times 10^{-3}\%$

$\sigma = 50.3$ (kPa)

⑦ $\gamma = 2.57 \times 10^{-3}\%$

$\sigma = 50.4$ (kPa)

⑧ $\gamma = 2.31 \times 10^{-3}\%$

$\sigma = 50.5$ (kPa)

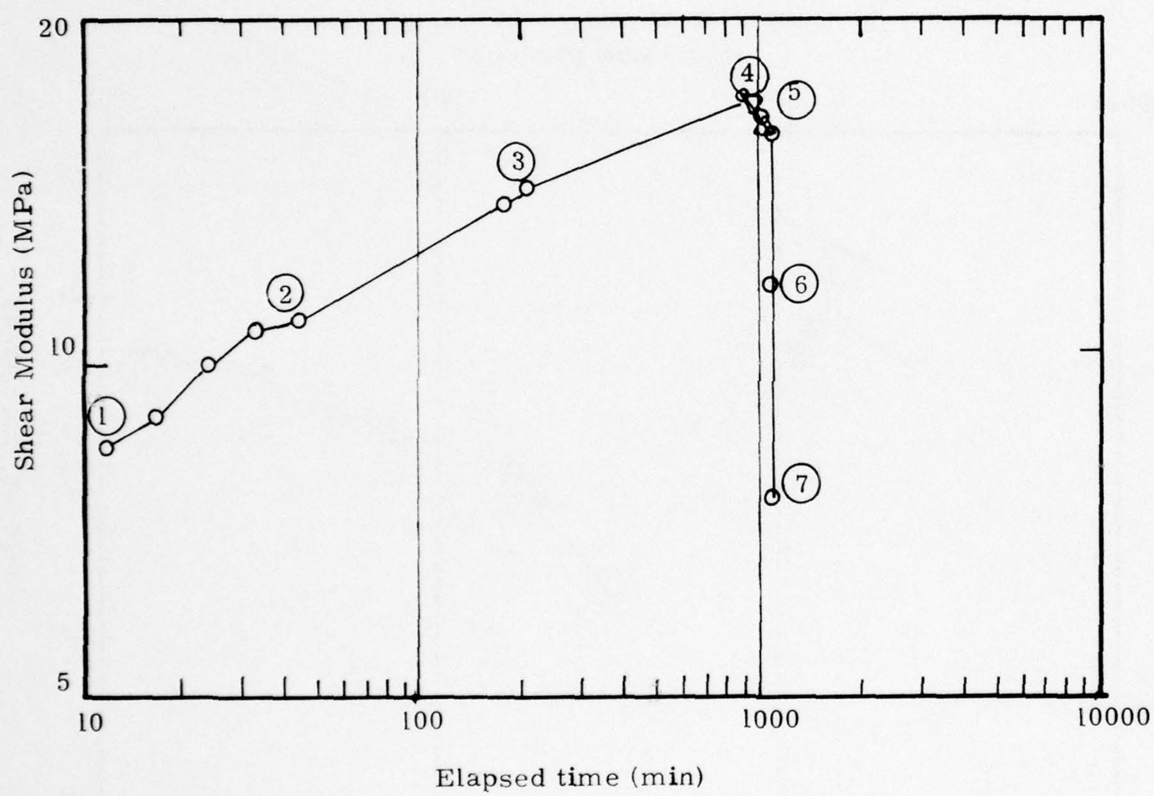
⑨ $\gamma = 2.06 \times 10^{-3}\%$

$\sigma = 82.4$ (kPa)

▽ BEGIN BACKPRESSURE

△ END BACKPRESSURE

Fig. 12. Shear Modulus versus Elapsed Time Resonant Column Sample JW6825 (Backebol)



(1) $\gamma = 4.33 \times 10^{-3}\%$
$\sigma_0 = 52.8$ (kPa)
(2) $\gamma = 2.05 \times 10^{-3}\%$
$\sigma = 52.1$ (kPa)
(3) $\gamma = 1.07 \times 10^{-3}\%$
$\sigma = 51.4$ (kPa)
(4) $\gamma = 1.06 \times 10^{-3}\%$
$\sigma = 51.1$ (kPa)
(5) $\gamma = 1.01 \times 10^{-3}\%$
$\sigma = 50.0$ (kPa)
(6) $\gamma = 62.75 \times 10^{-3}\%$
$\sigma = 51.0$ (kPa)
(7) $\gamma = 288.29 \times 10^{-3}\%$
$\sigma = 49.0$ (kPa)

∇ BEGIN BACKPRESSURE
Δ END BACKPRESSURE

Fig. 13. Shear Modulus versus Elapsed Time
Resonant Column Sample JW6825B

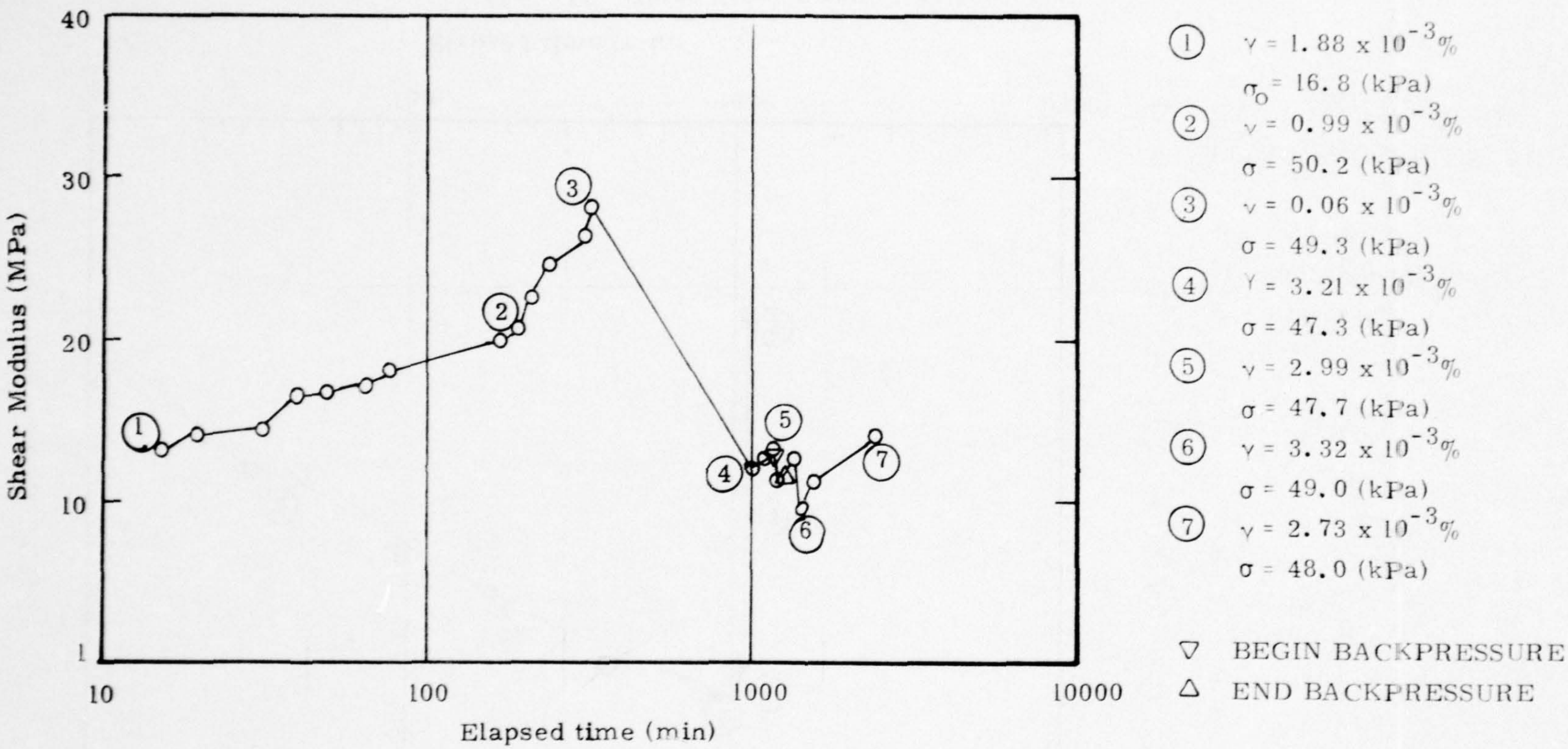


Fig. 14. Shear Modulus versus Elapsed Time
Resonant Column Sample 6249 (Norrkoping)

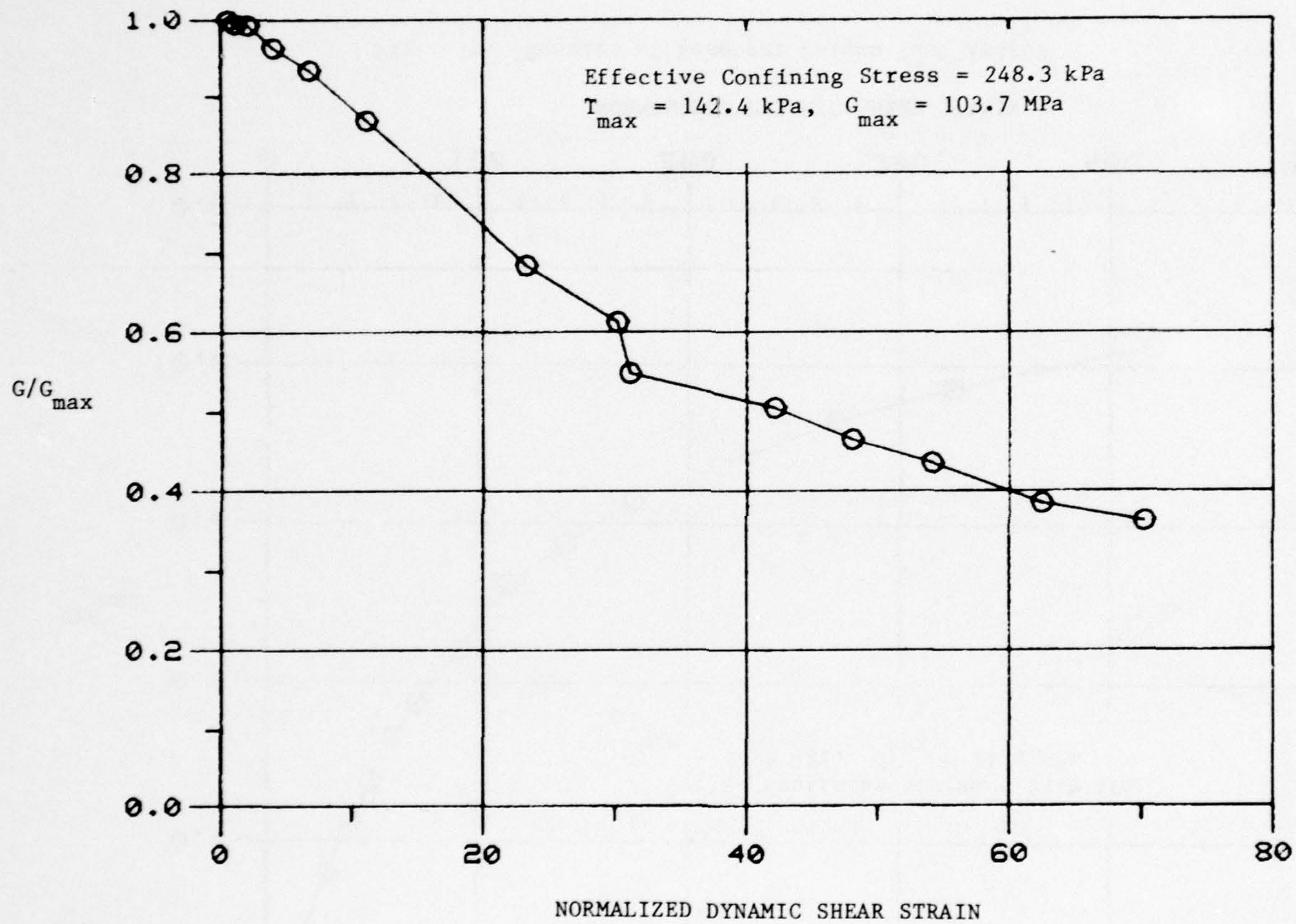


Fig. 15. Results of Resonant Column Test KYD1A

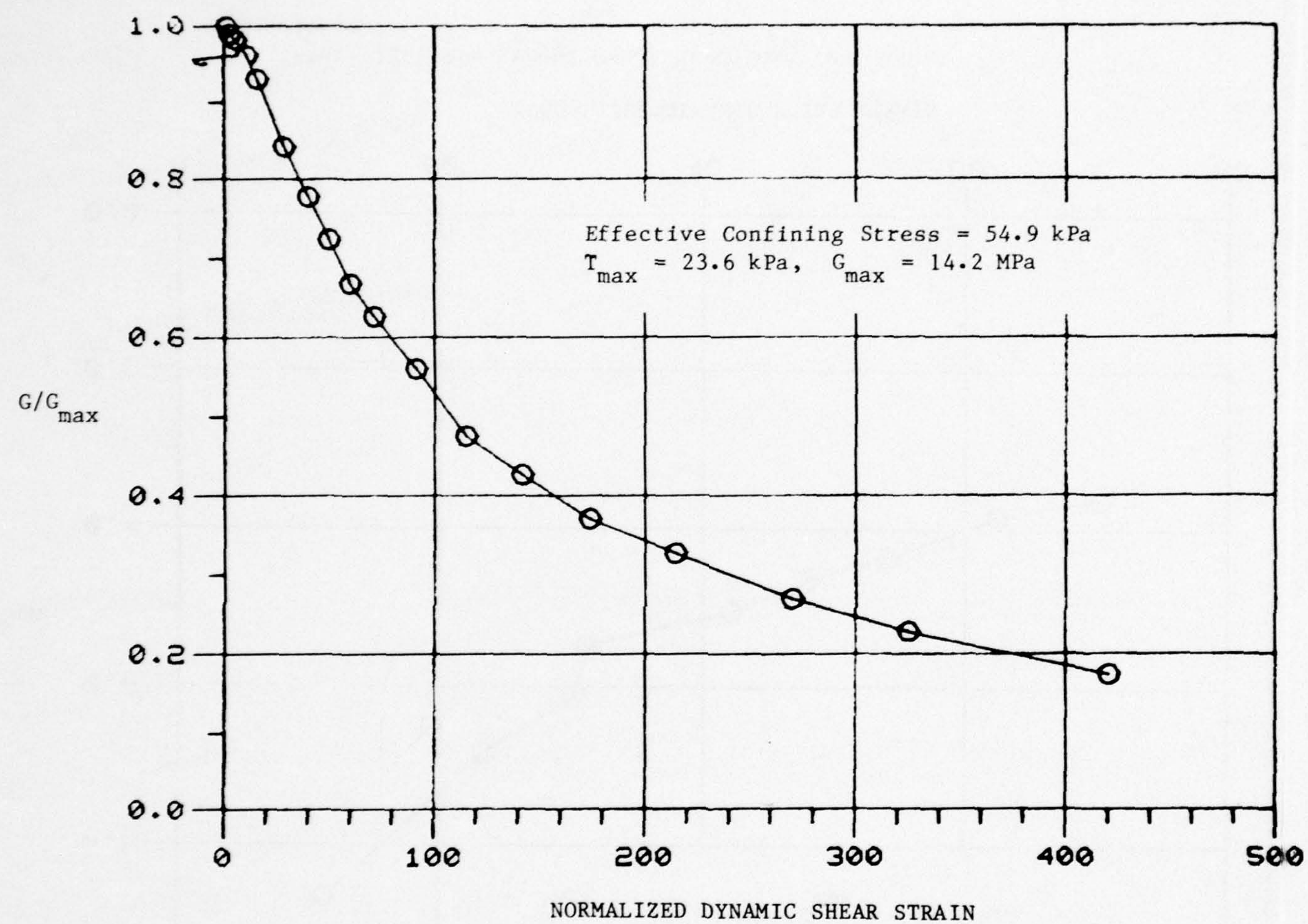


Fig. 16. Results of Resonant Column Test JW3260

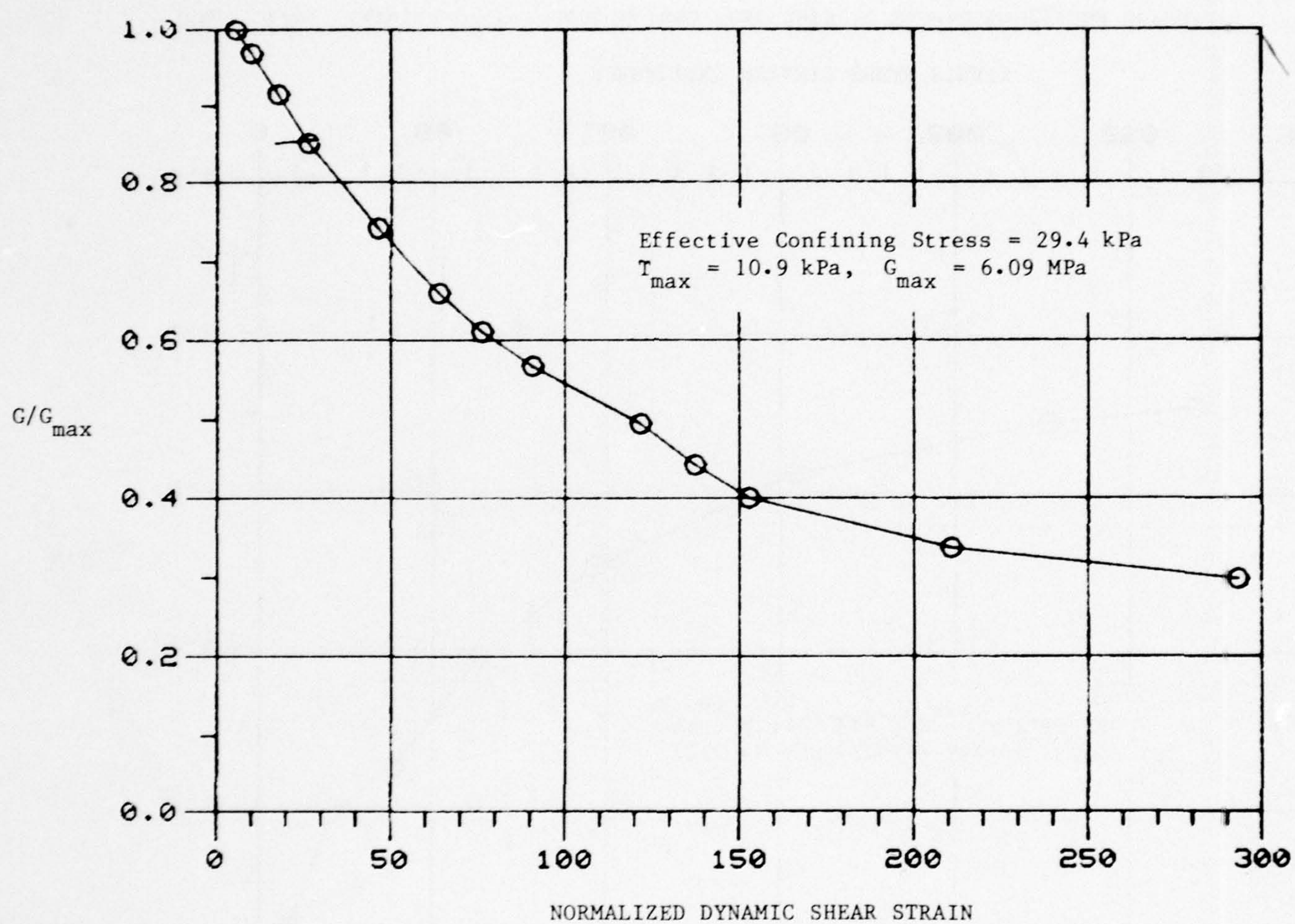


Fig. 17a. Results of Resonant Column Test S-19 at First Confining Stress

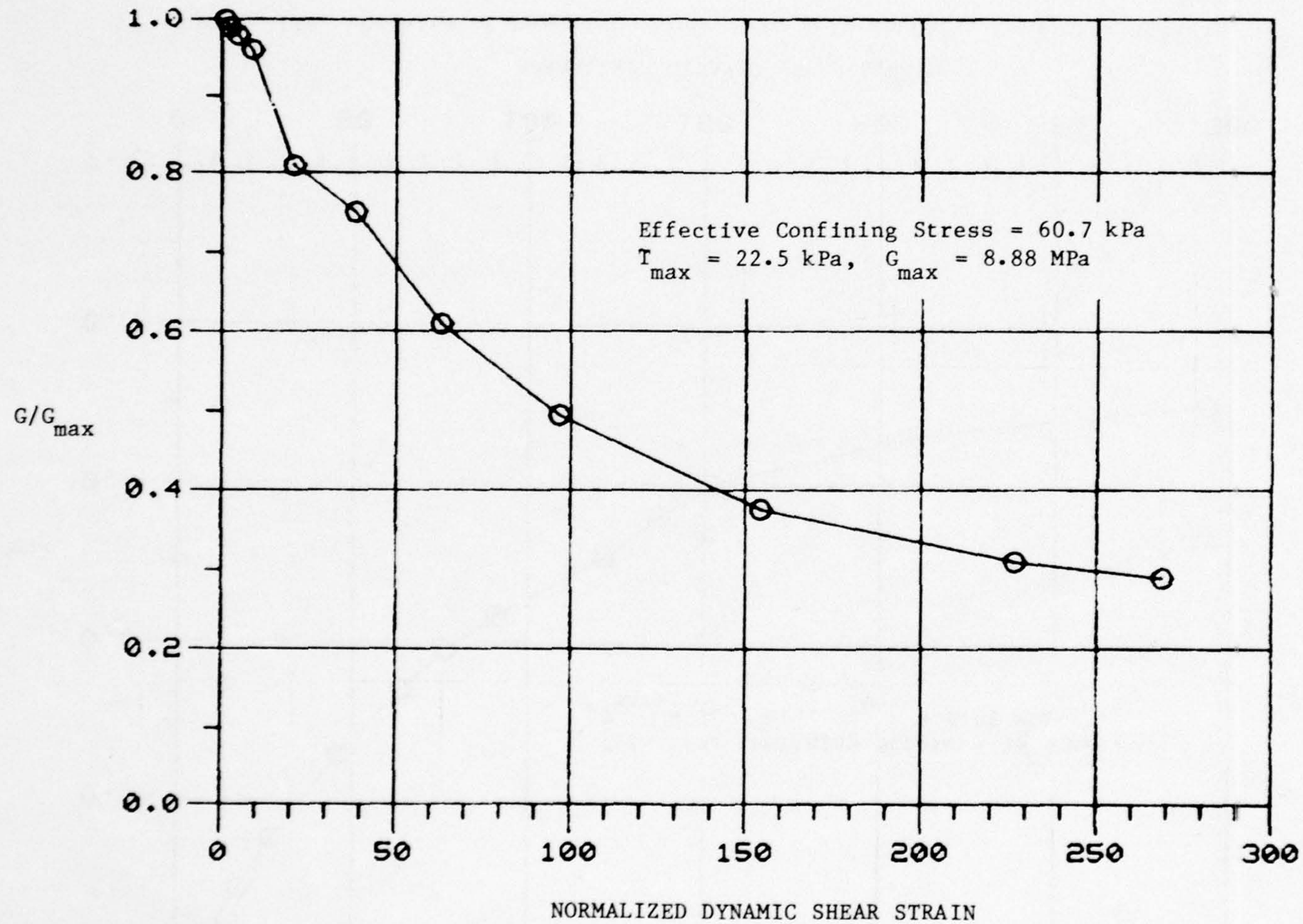


Fig. 17b. Results of Resonant Column Test S-19 at Second Confining Stress

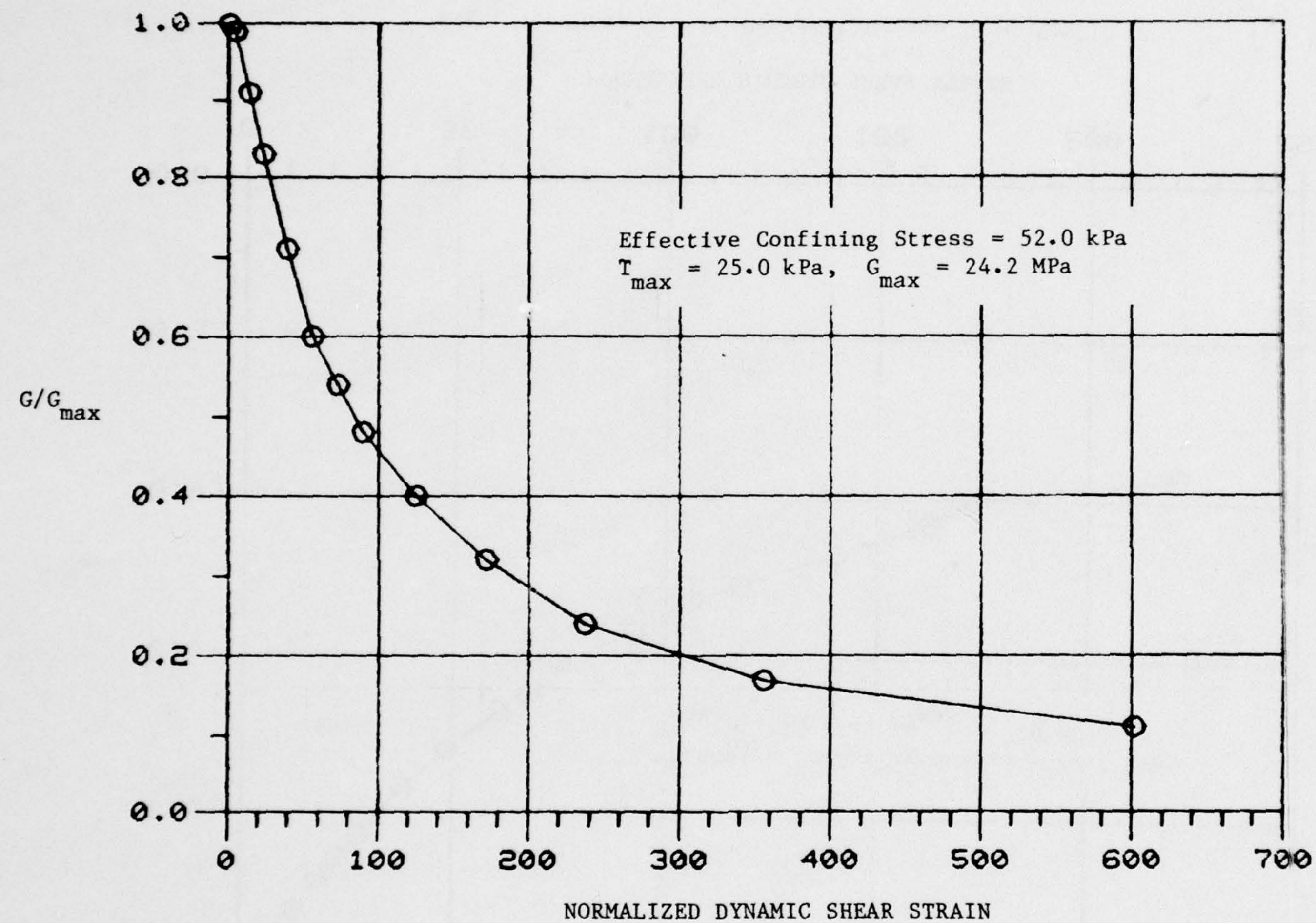


Fig. 18. Results of Resonant Column Test A-1 (Drammen Clay)

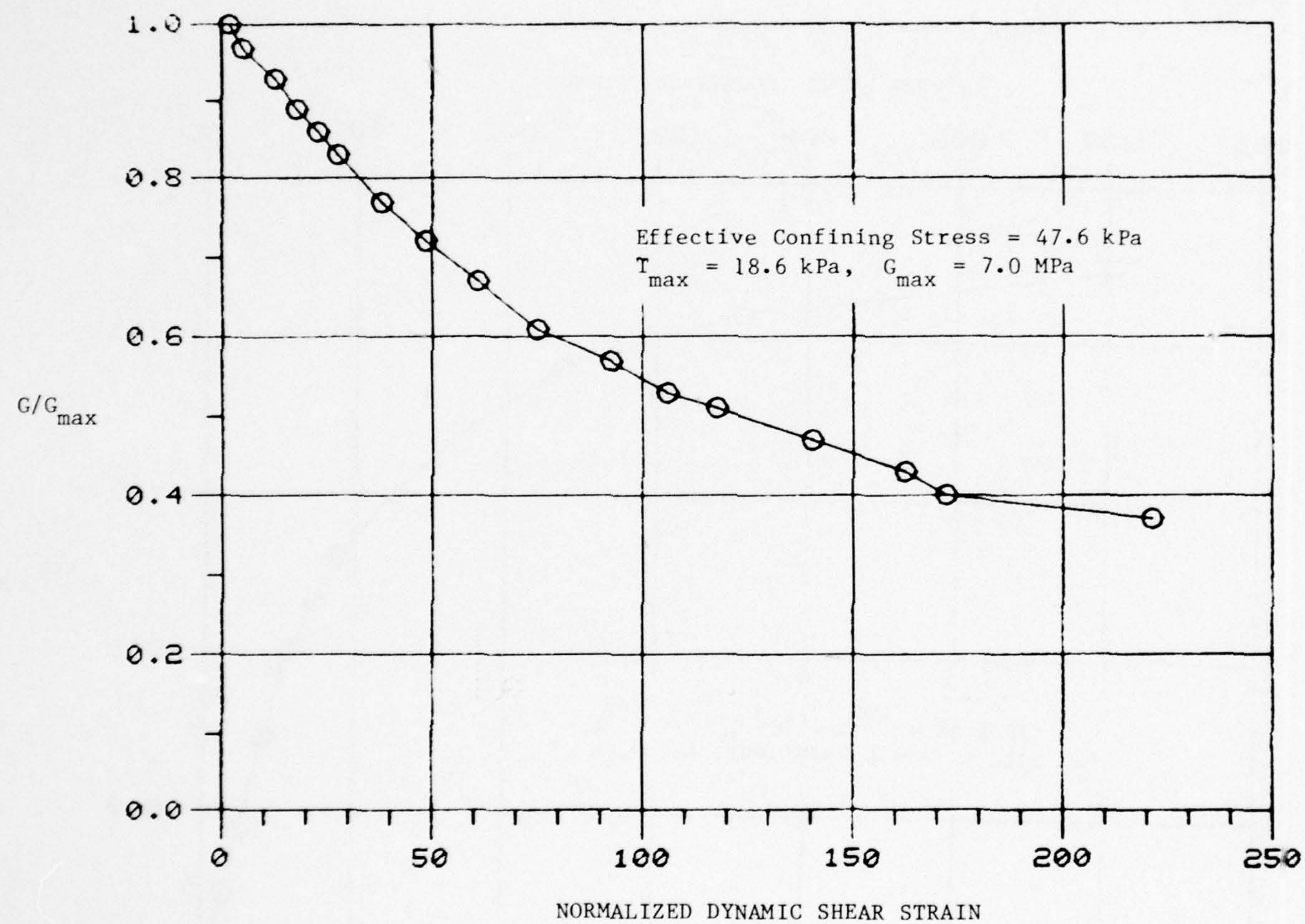


Fig. 19. Results of Resonant Column Test JW5337

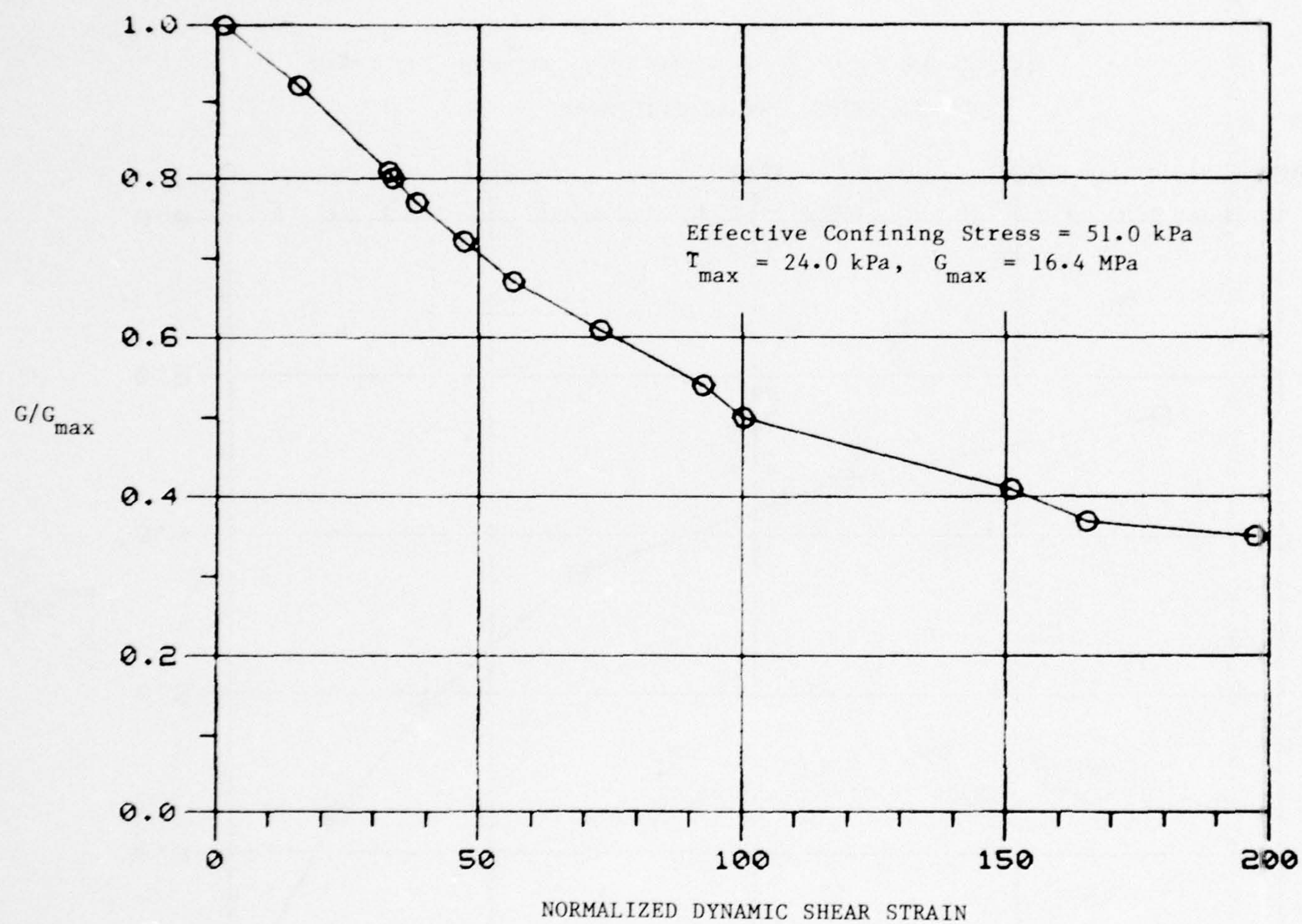


Fig. 20. Results of Resonant Column Test JW6825

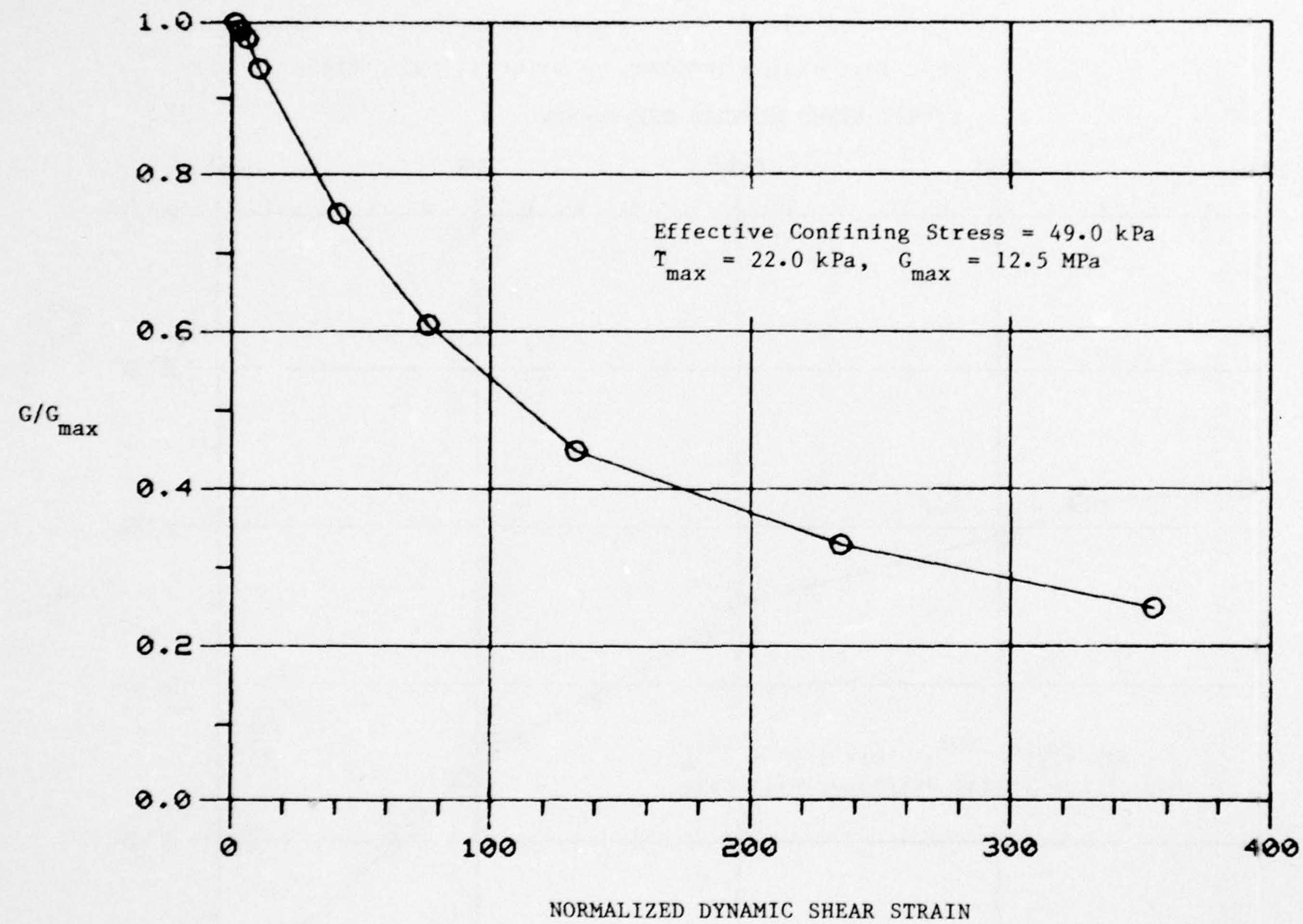


Fig. 21. Results of Resonant Column Test SGI (6249)

AD-A077 913   KENTUCKY UNIV LEXINGTON DEPT OF CIVIL ENGINEERING   F/G 8/13
EVALUATION OF SAMPLE DISTURBANCE ON SOILS USING THE CONCEPT OF --ETC(U)
SEP 79   V P DRNEVICH   DACW39-78-C-0046

UNCLASSIFIED   WES/GL-79-13   NL

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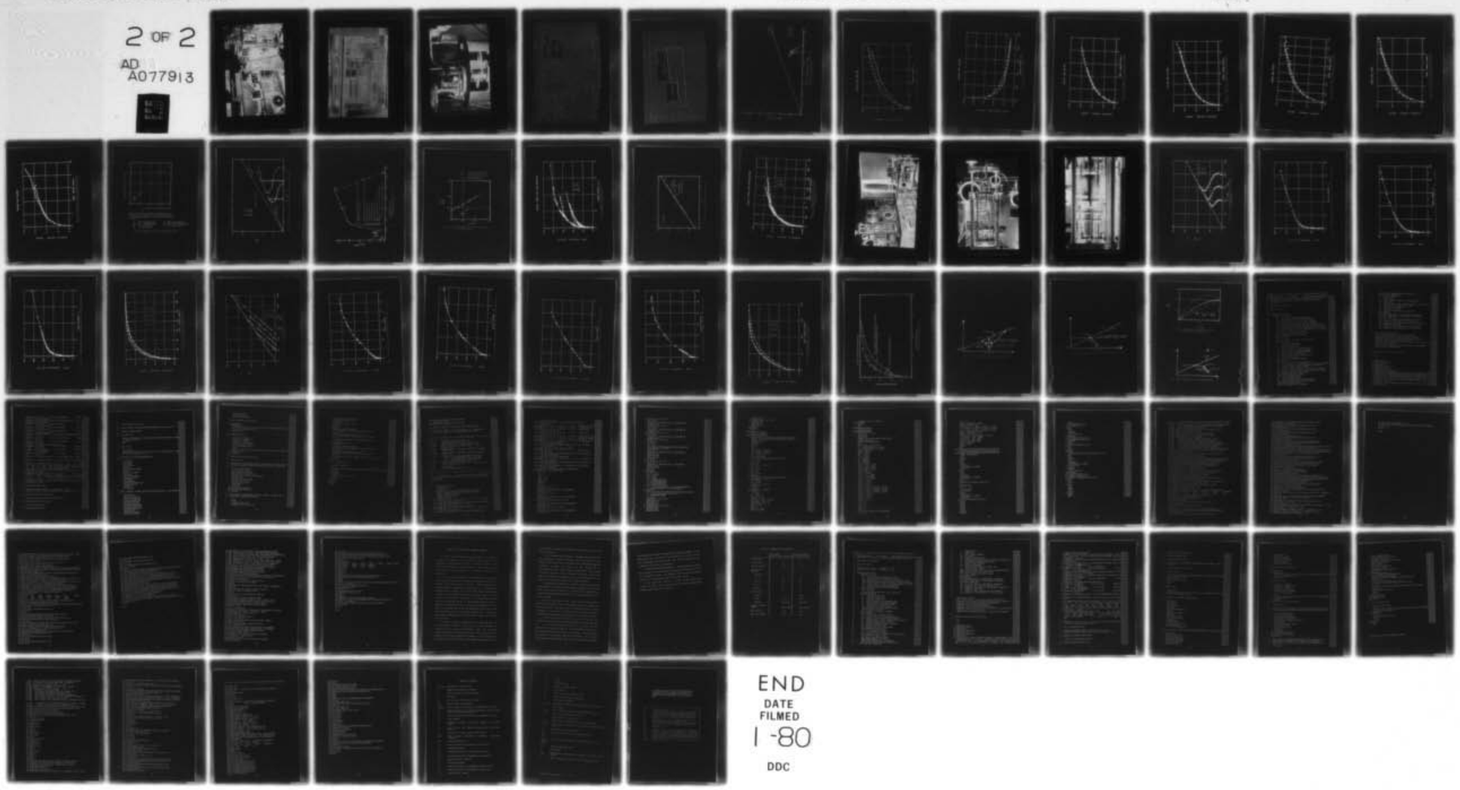

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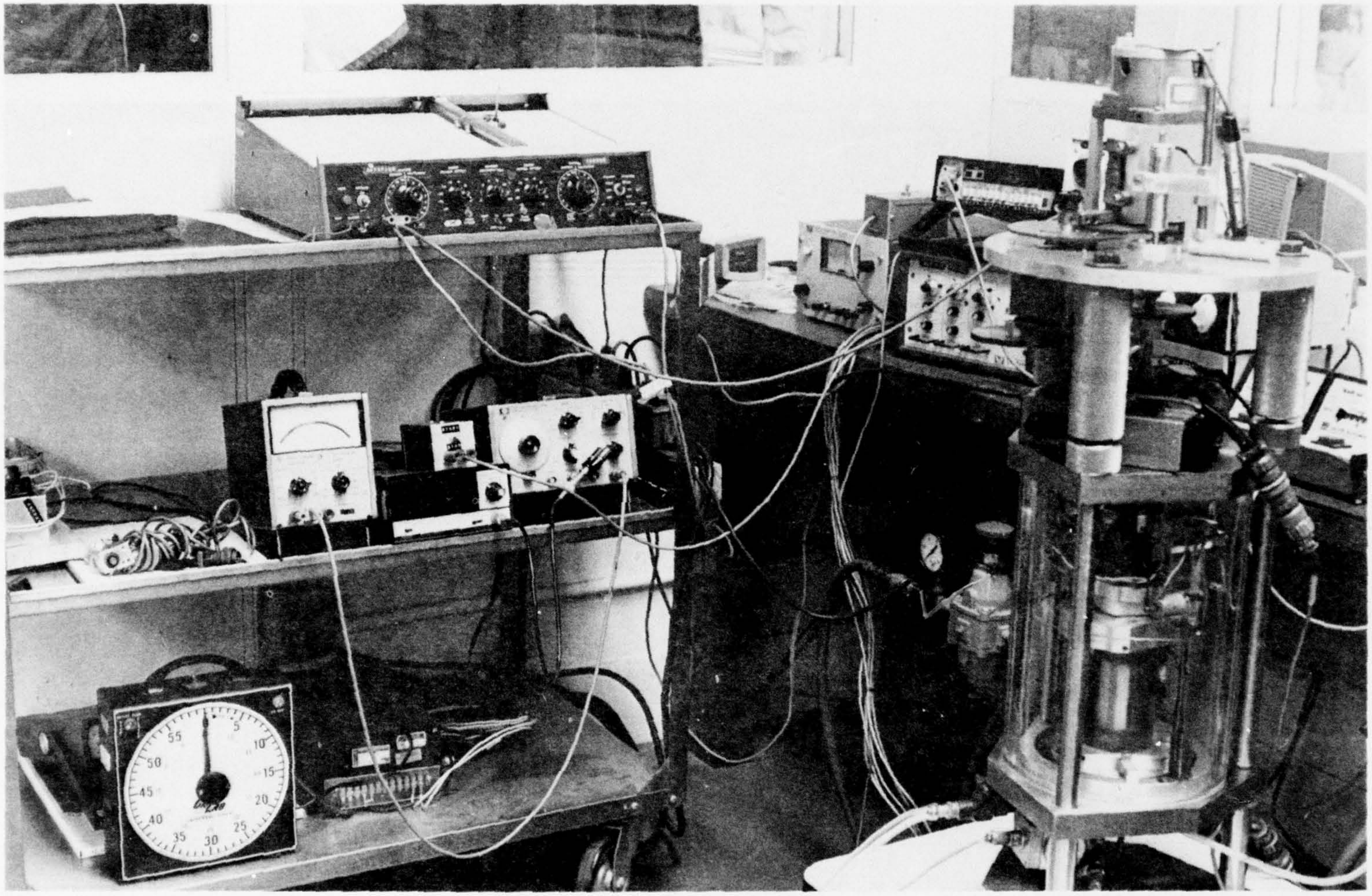


Fig. 22. Overview of Torsional Simple Shear Apparatus and Electronics

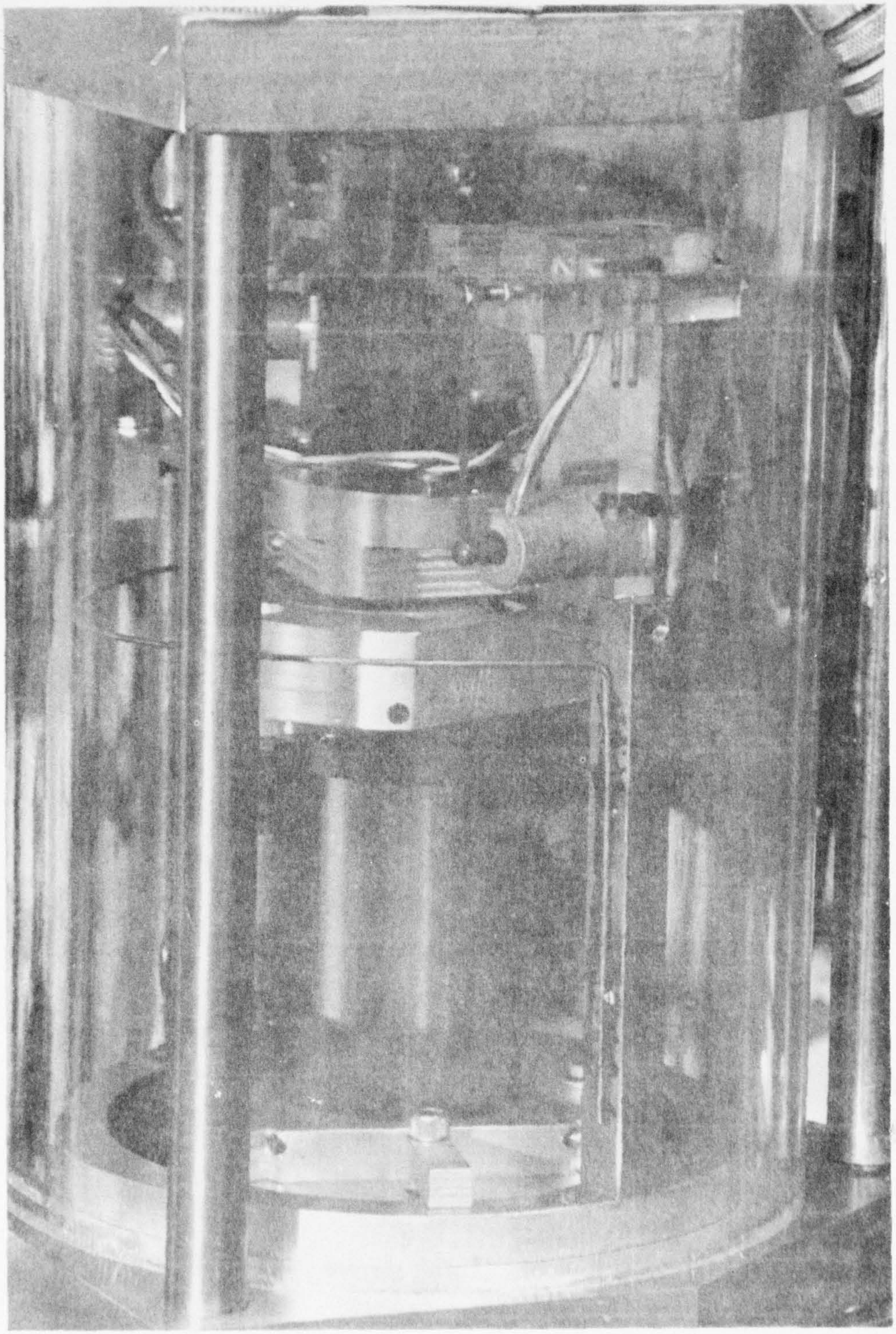


Fig. 23. Specimen, Supporting Clamp, and Transducers of Torsional Simple Shear Apparatus

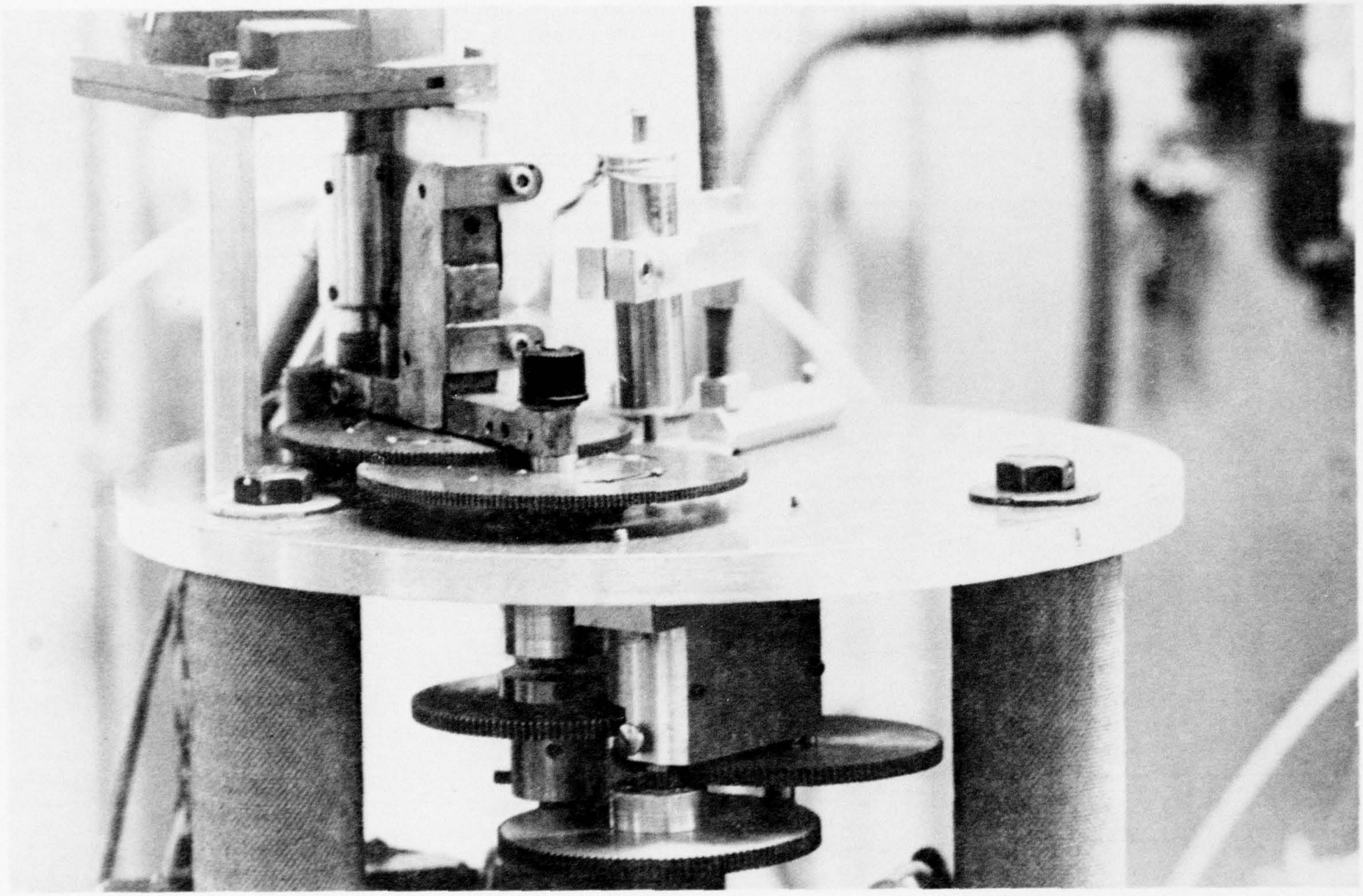


Fig. 24. Close-up View of Gear Reduction System

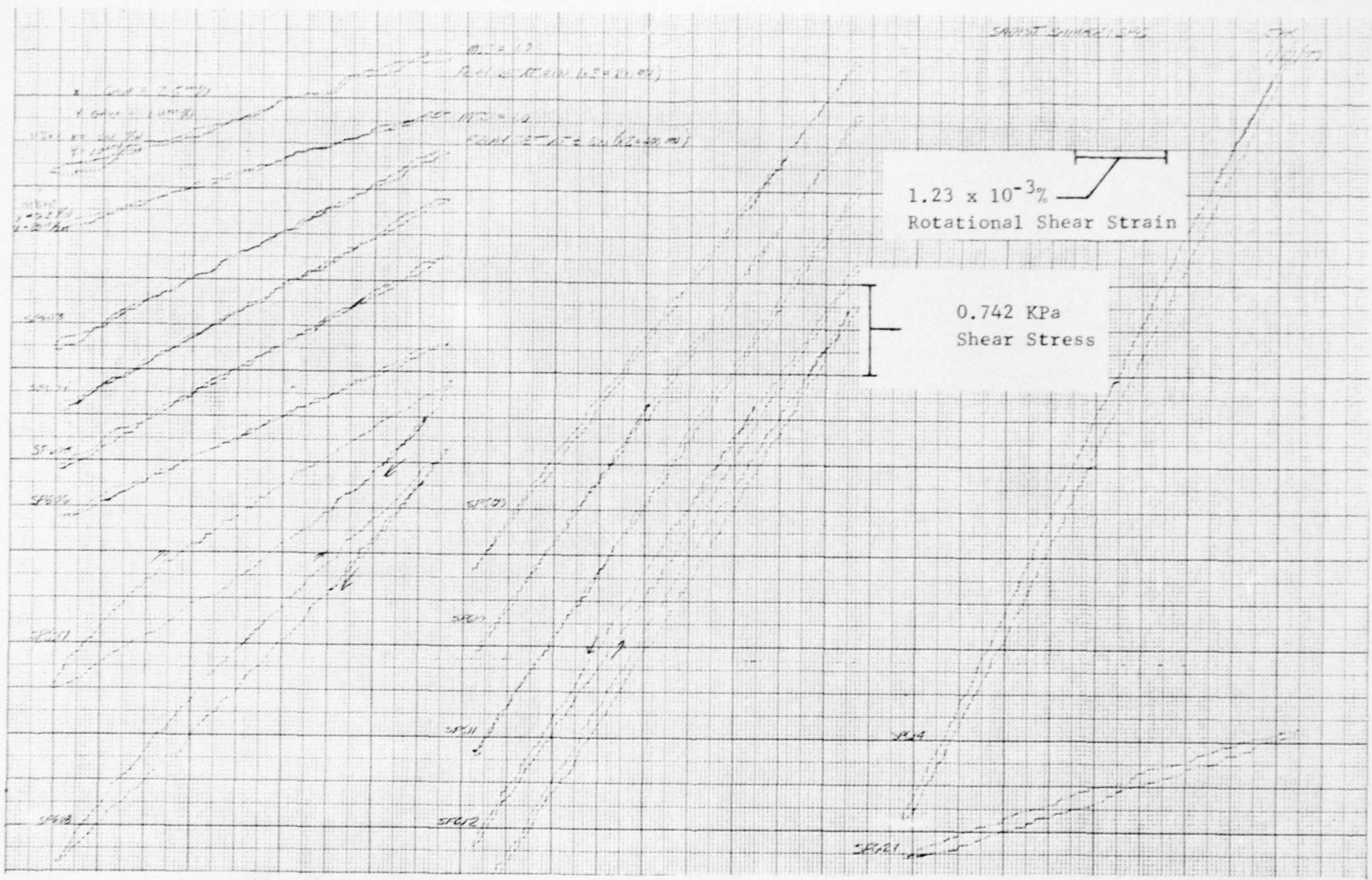


Fig. 25. Typical Recordings at Low Shear Strain Amplitudes to Measure Initial Tangent Moduli with Torsional Simple Shear

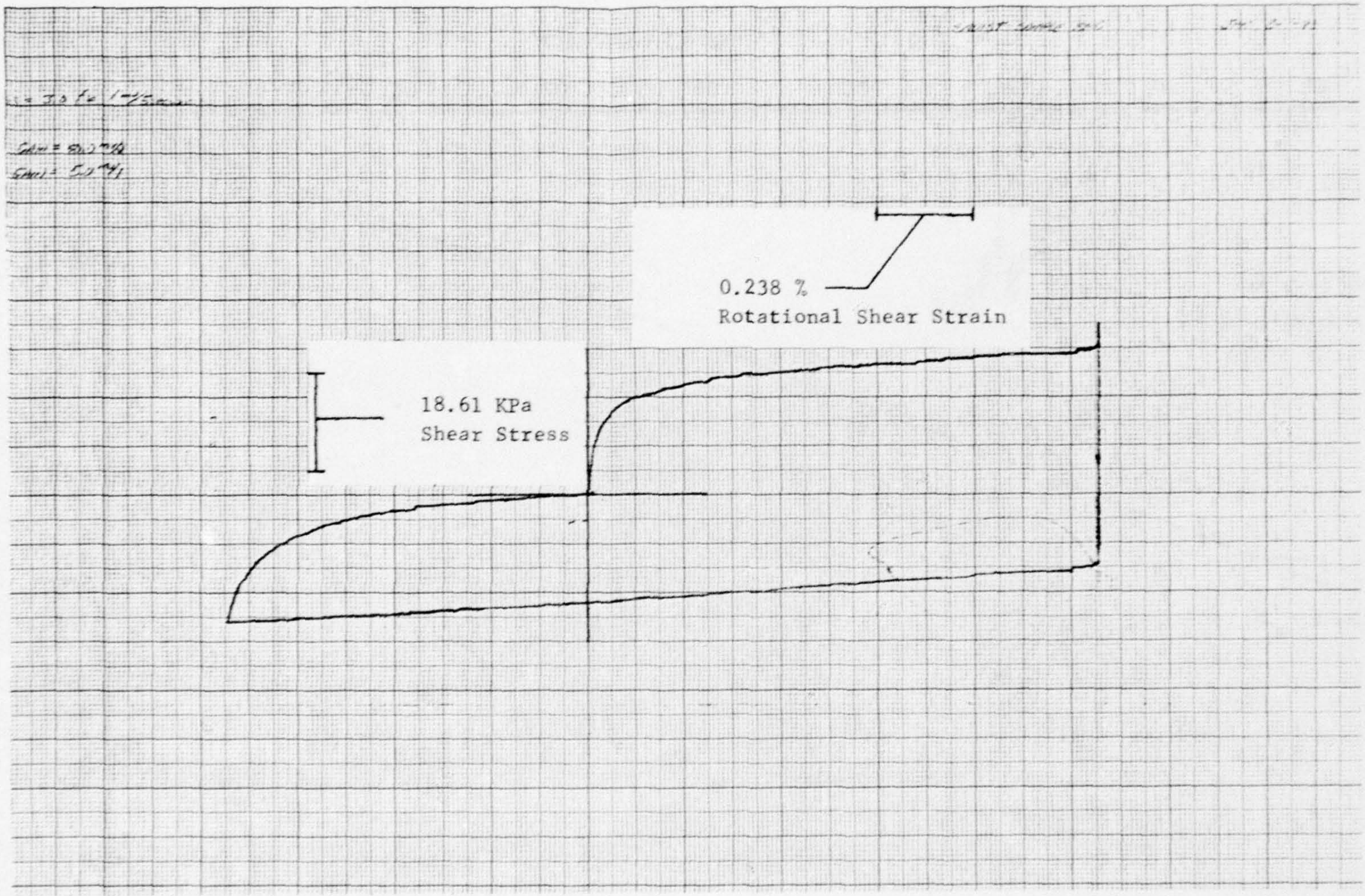


Fig. 26. Typical Recording of Large Amplitude Torsional Simple Shear Test

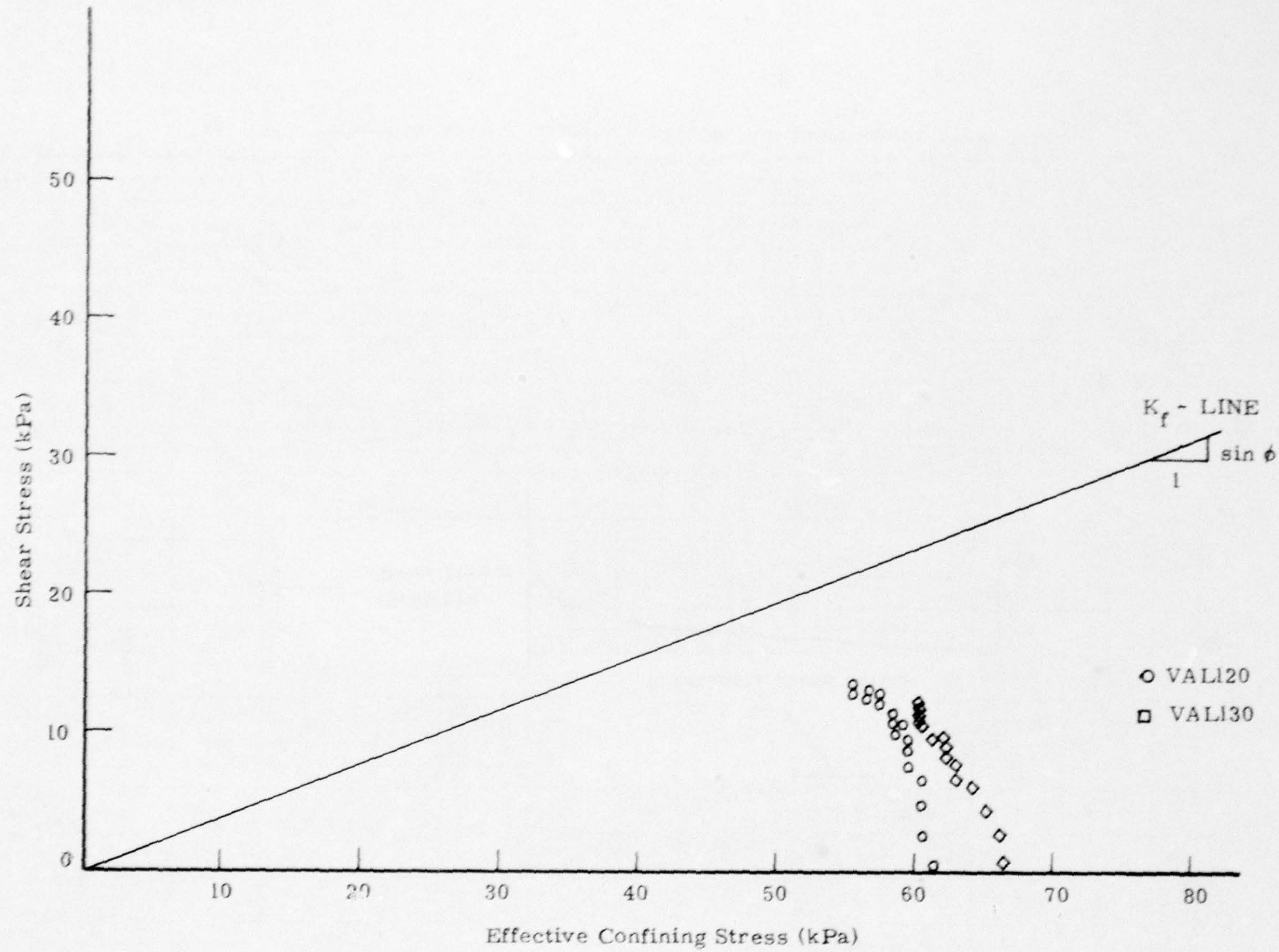


Fig. 27. Typical Stress Paths for Torsional Simple Test on Undisturbed Soils

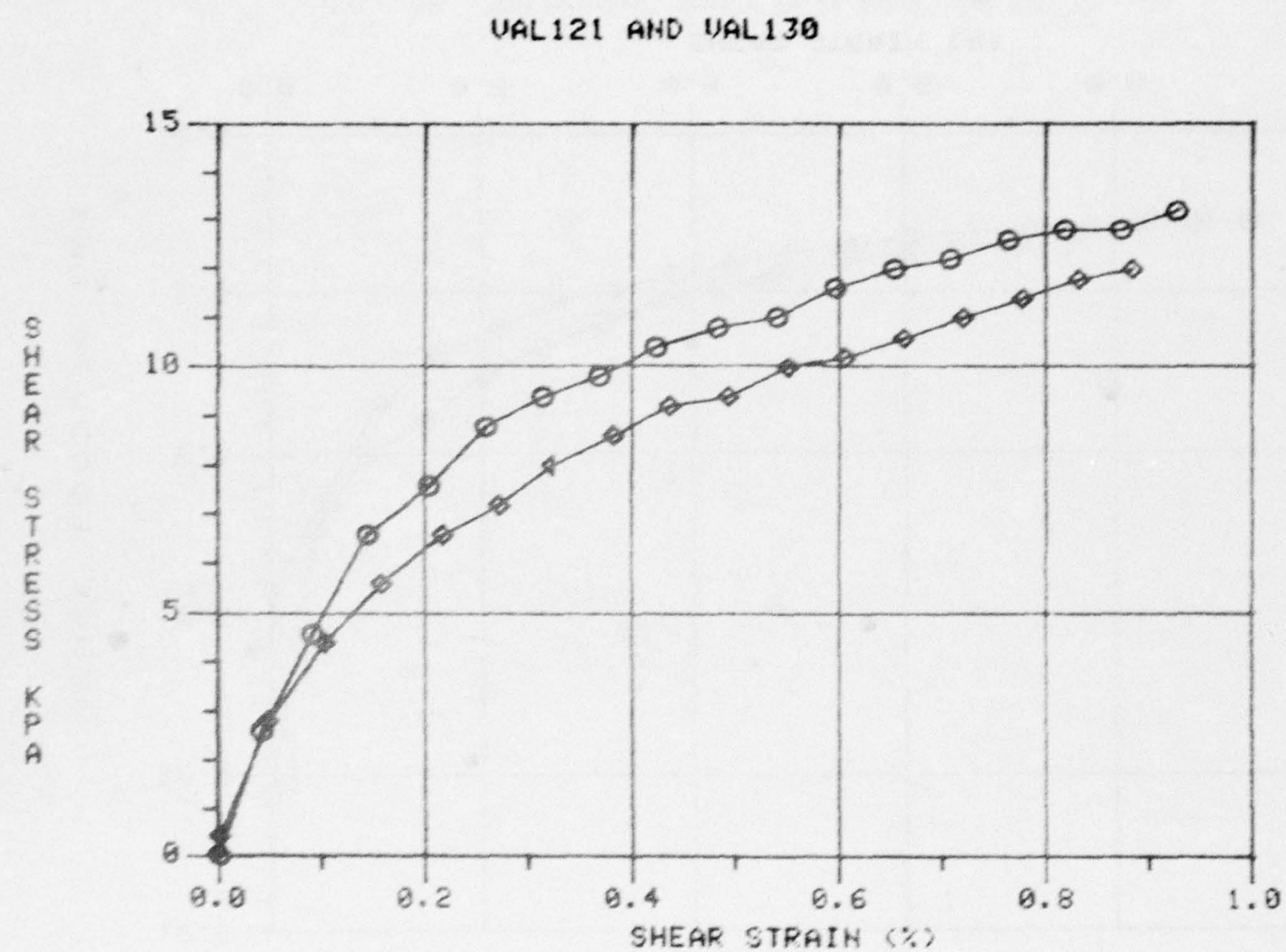


Fig. 28. "Undisturbed" Sample Tests VAL121 and VAL130
Shear Stress versus Shear Strain

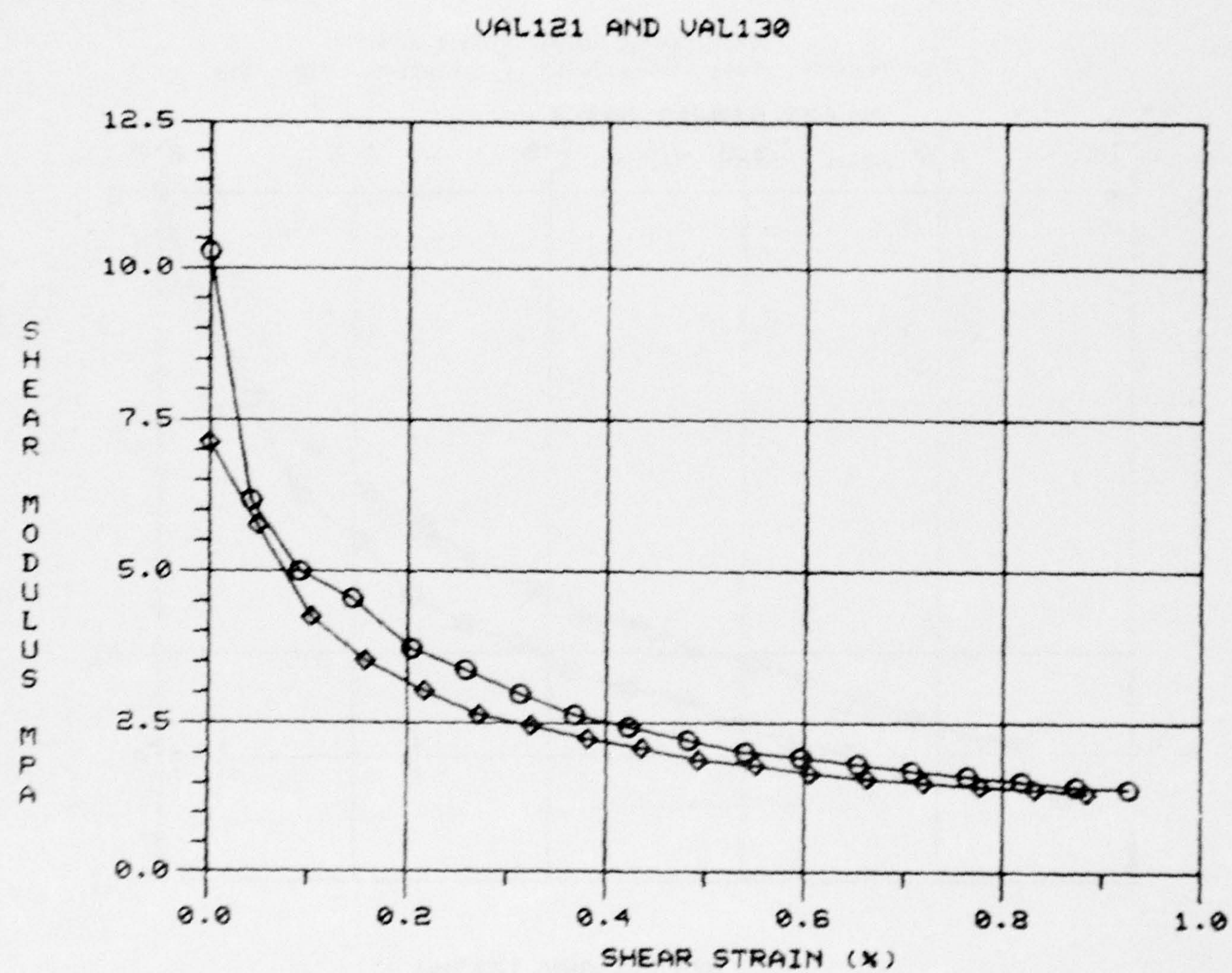


Fig. 29. "Undisturbed" Sample Tests VAL121 and VAL130
Shear Modulus versus Shear Strain

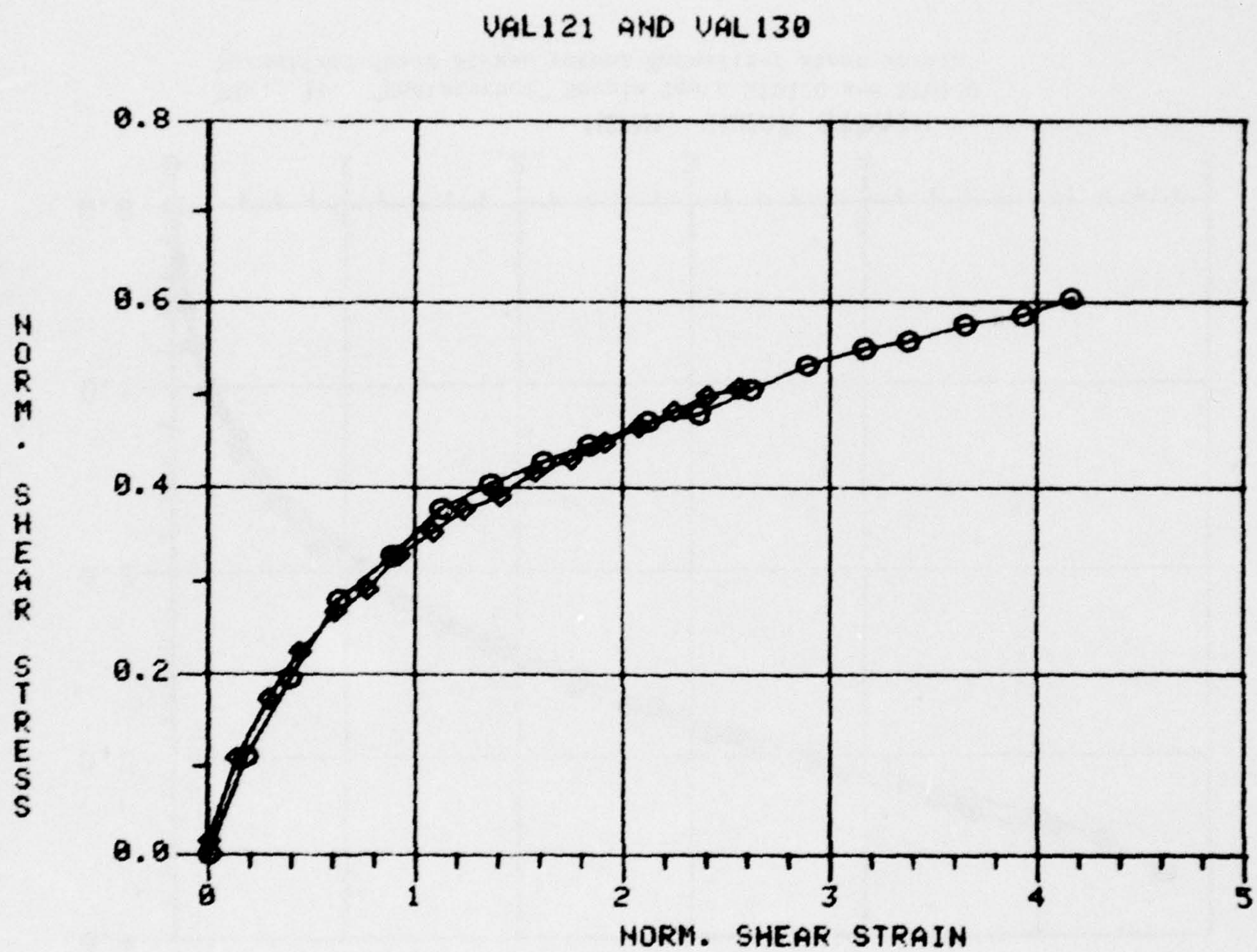


Fig. 30. "Undisturbed" Sample Tests VAL121 and VAL130
Normalized Shear Stress versus Normalized Shear Strain

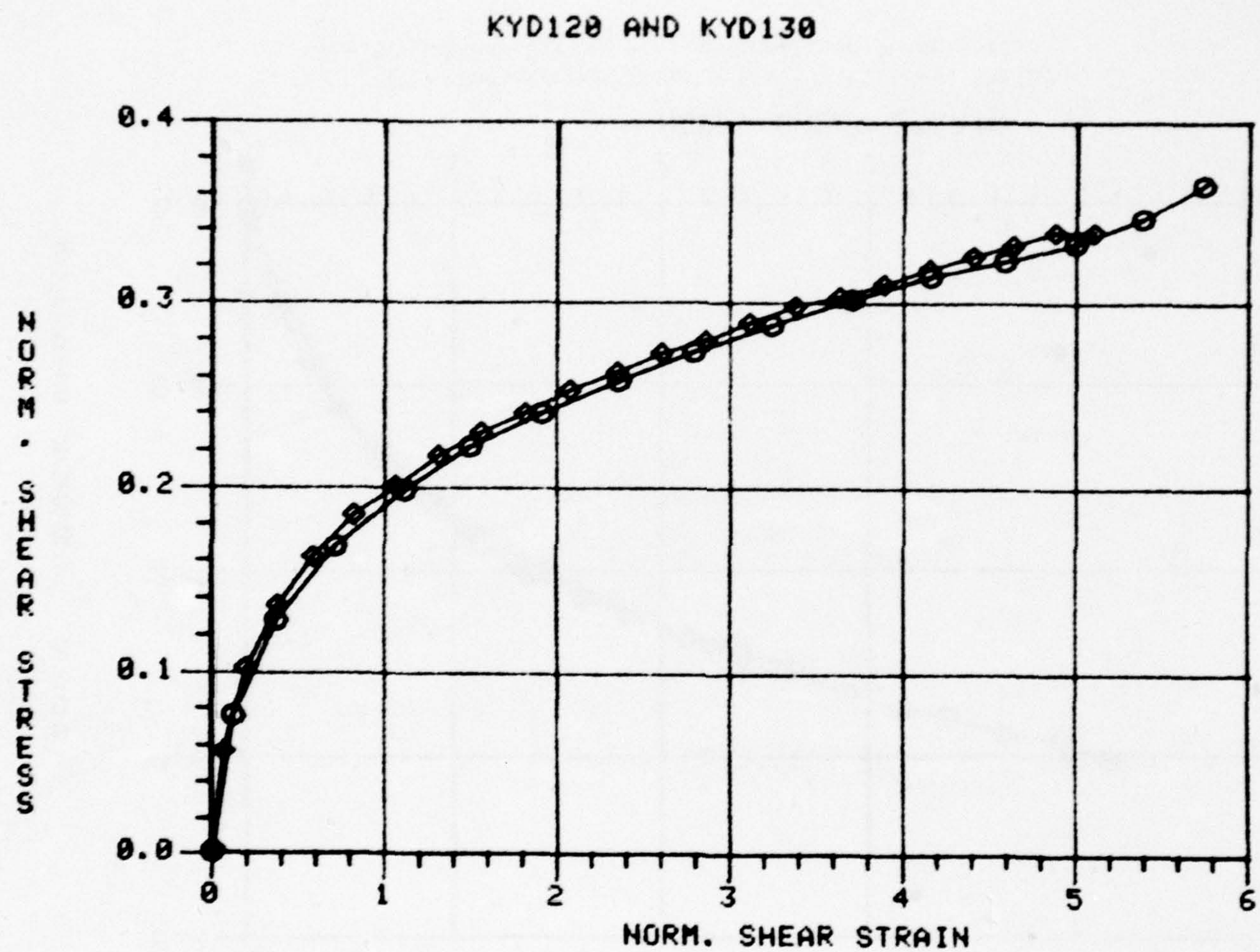


Fig. 31. "Undisturbed" Sample Tests KYD120 and KYD130
Normalized Shear Stress versus Normalized Shear Strain

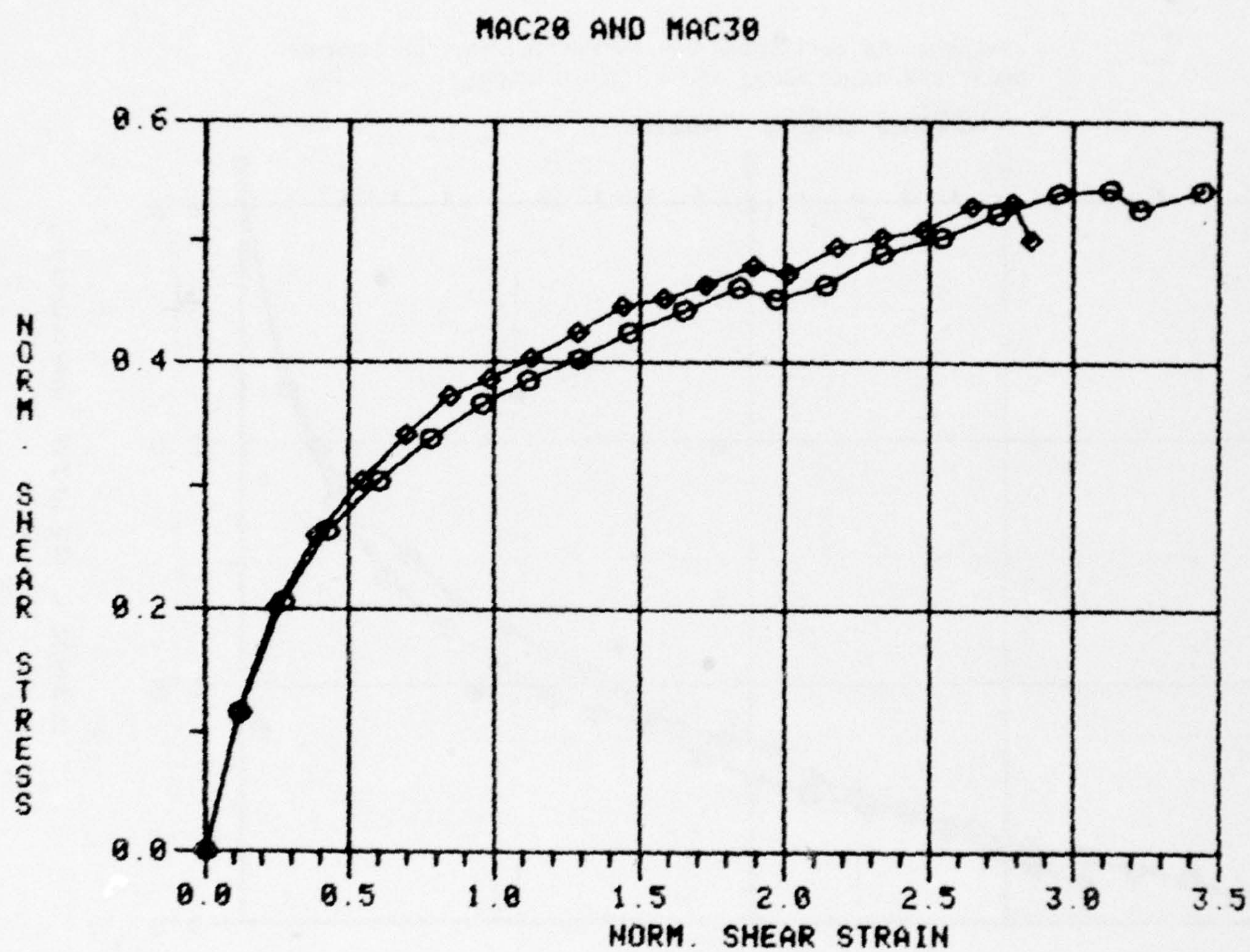


Fig. 32. "Undisturbed" Sample Tests MAC20 and MAC30
Normalized Shear Stress versus Normalized Shear Strain

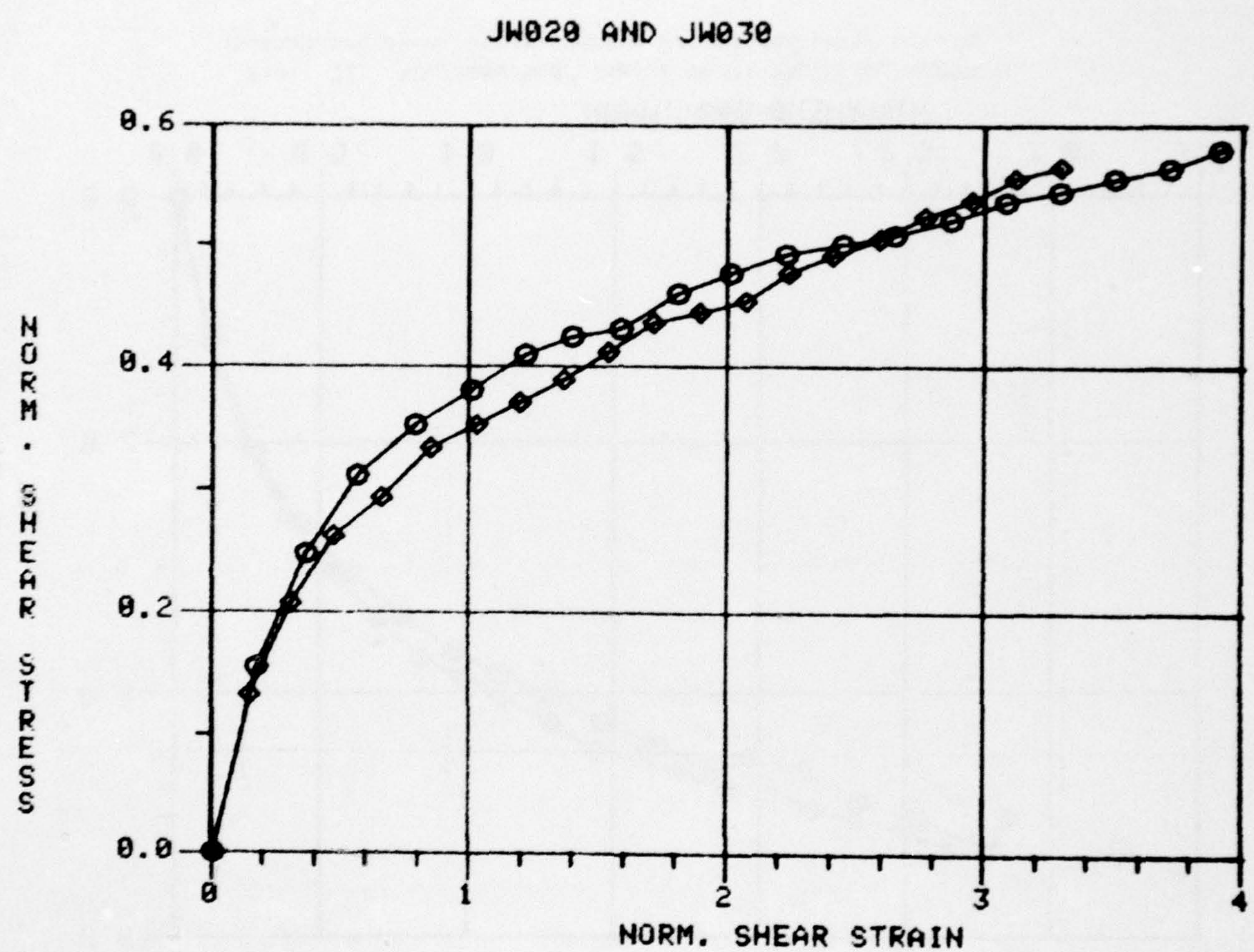


Fig. 33. "Undisturbed" Sample Tests JW020 and JW030
Normalized Shear Stress versus Normalized Shear Strain

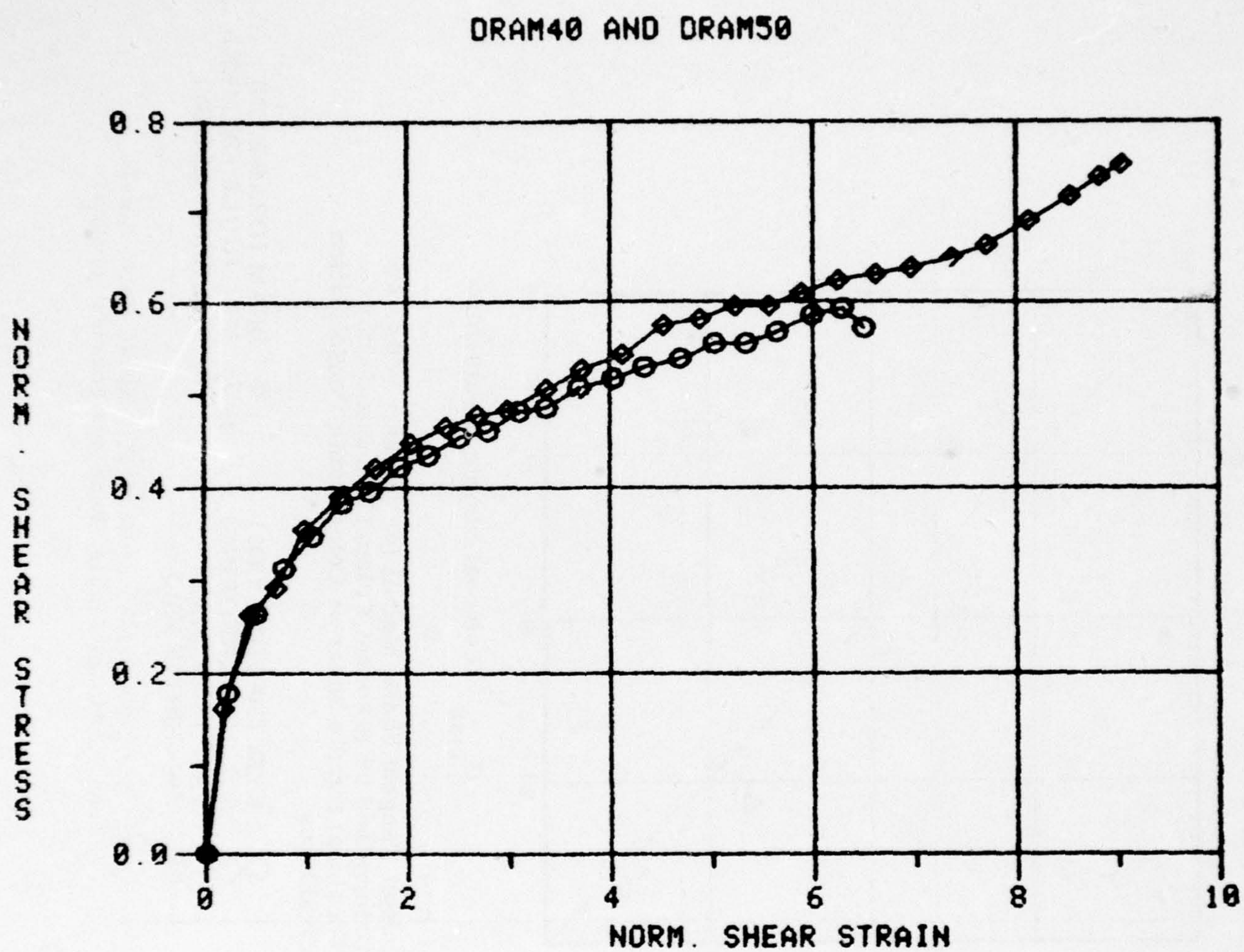
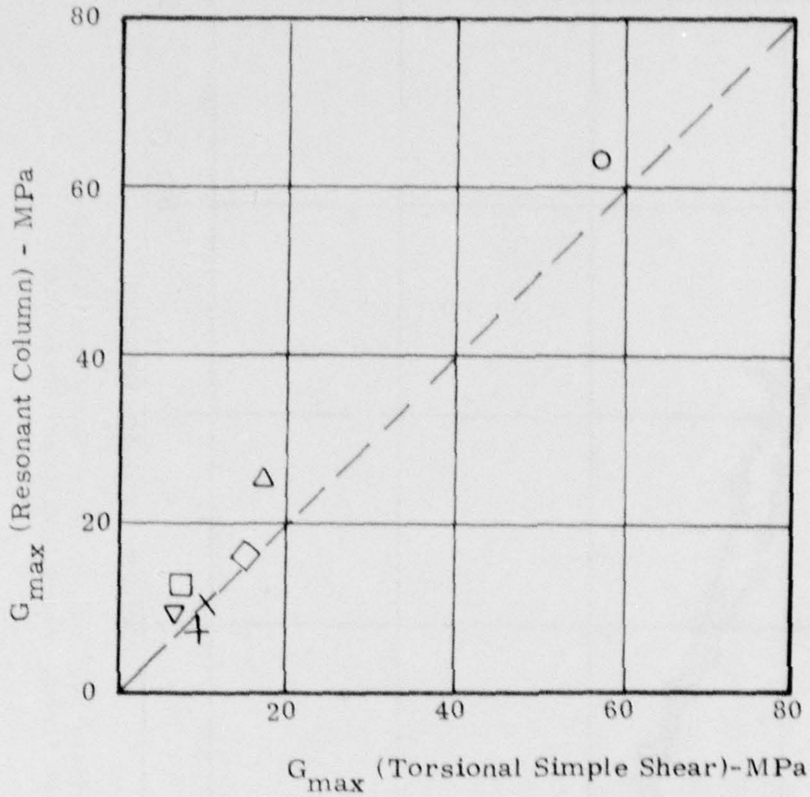


Fig. 34. "Undisturbed" Sample Tests DRAM40 and DRAM50 Normalized Shear Stress versus Normalized Shear Strain



Initial Tangent Shear Moduli for Various Soils, As Determined by Resonant Column and Quasi-Static Torsional Simple Shear at Comparable Consolidation Conditions

○ KYDI (DAVIESS CO.)
◇ SGI (NORRKOPING)
+ VAL-1 (VALEN)
□ JW (BACKEBOL)
△ DRAM (DRAMMEN)
▽ MAC (GULF OF MEXICO)
× SKA (SKA-EDEBY)

Fig. 35. Comparison of Initial Tangent Shear Moduli from Torsional Simple Shear and Resonant Column

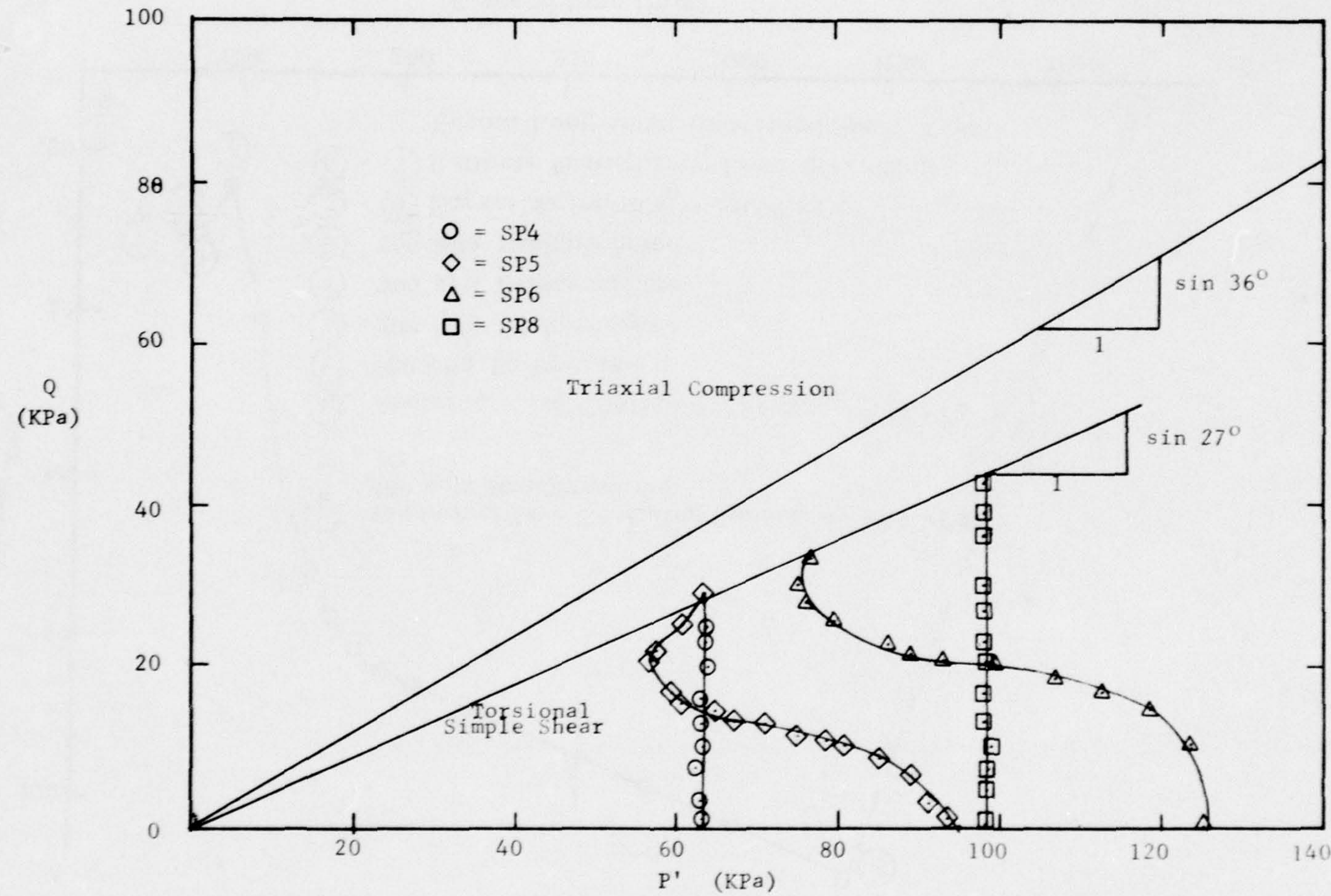


Fig. 36. Stress Paths for Torsional Simple Shear Tests on Remolded Soil

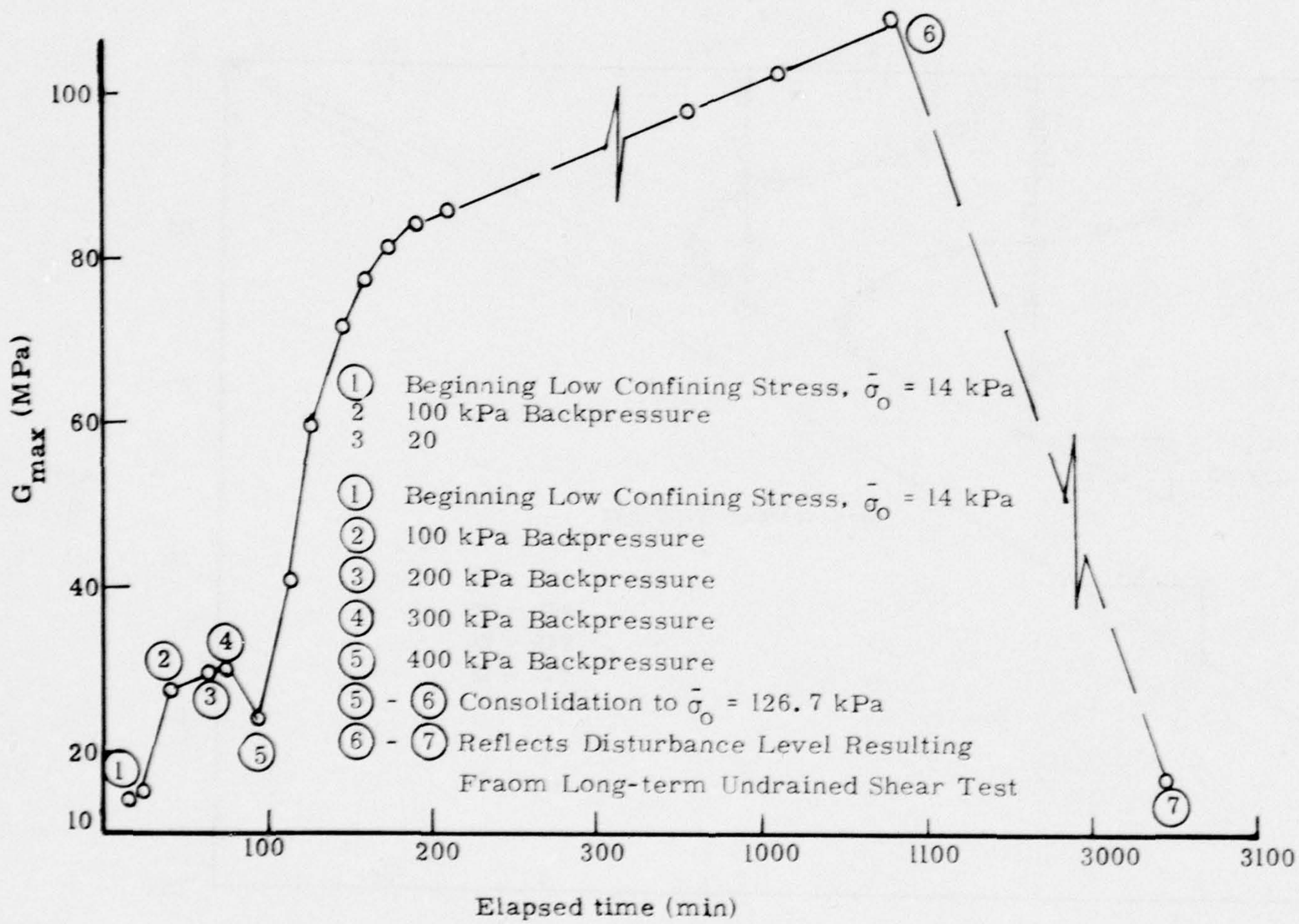


Fig. 37. Remolded Sample SP6 Variation of G_{max} with Testing Procedures

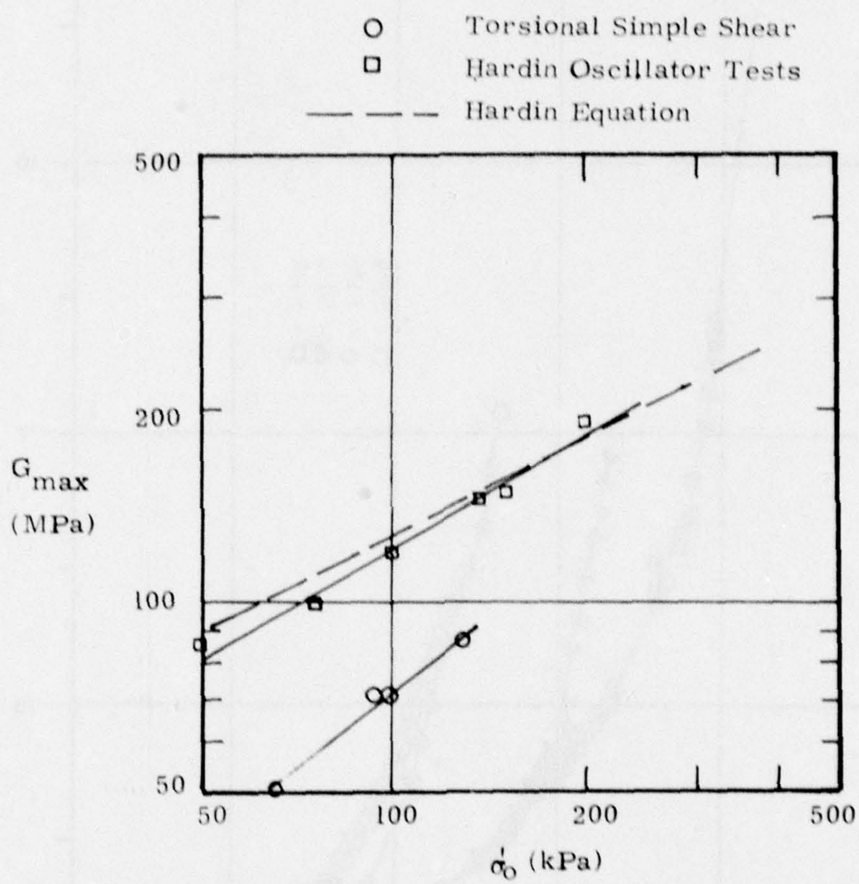


Fig. 38. Initial Tangent Shear Moduli for Remolded Soil Specimens

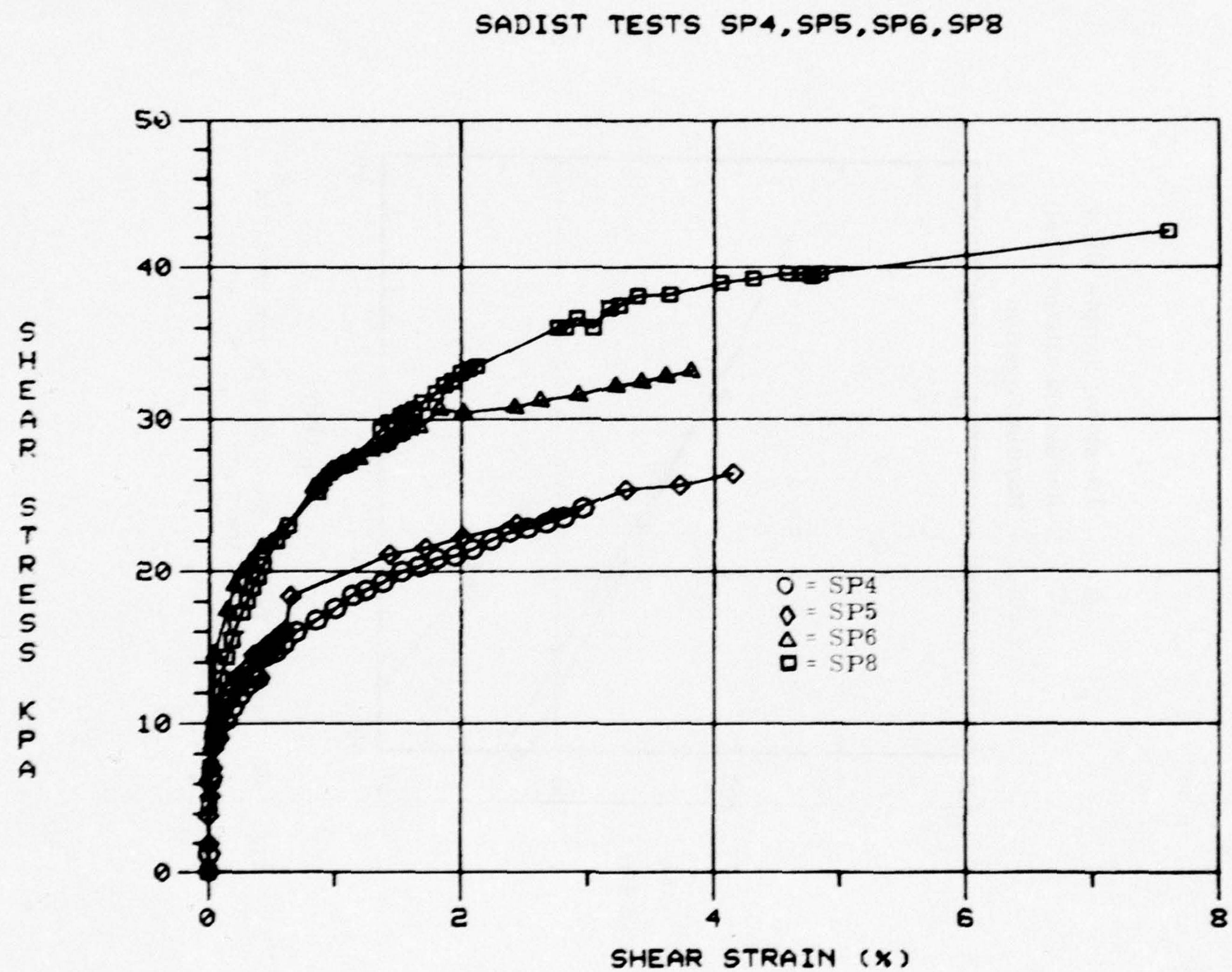


Fig. 39. Remolded Samples SP4, SP5, SP6, SP8
Shear Stress versus Shear Strain

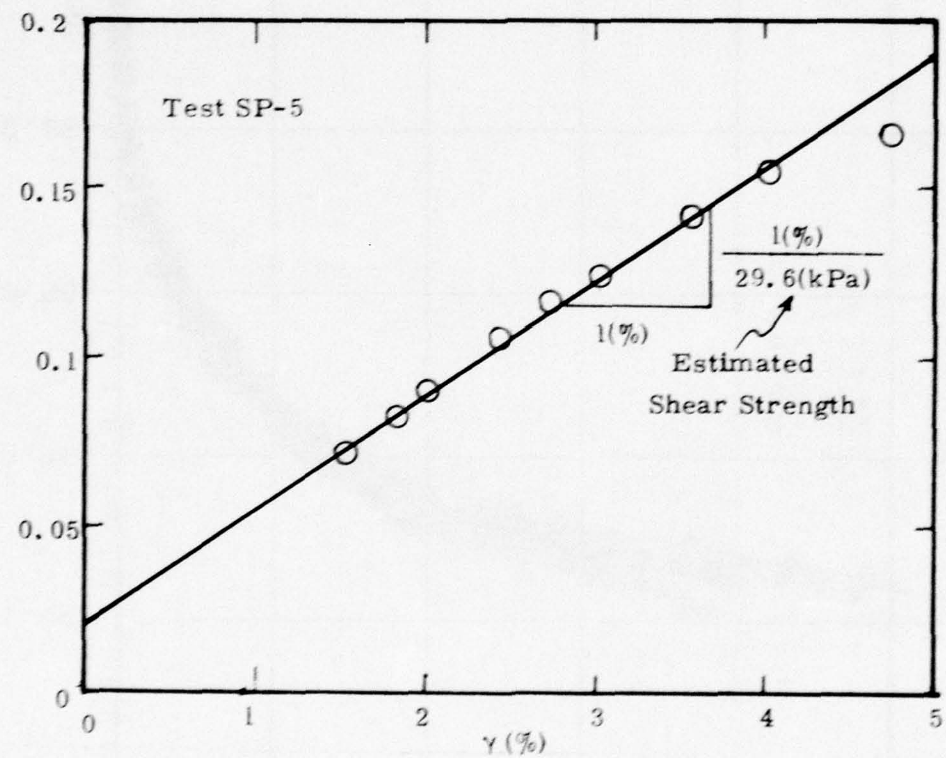


Fig. 40. Technique for Estimating Shear Strength

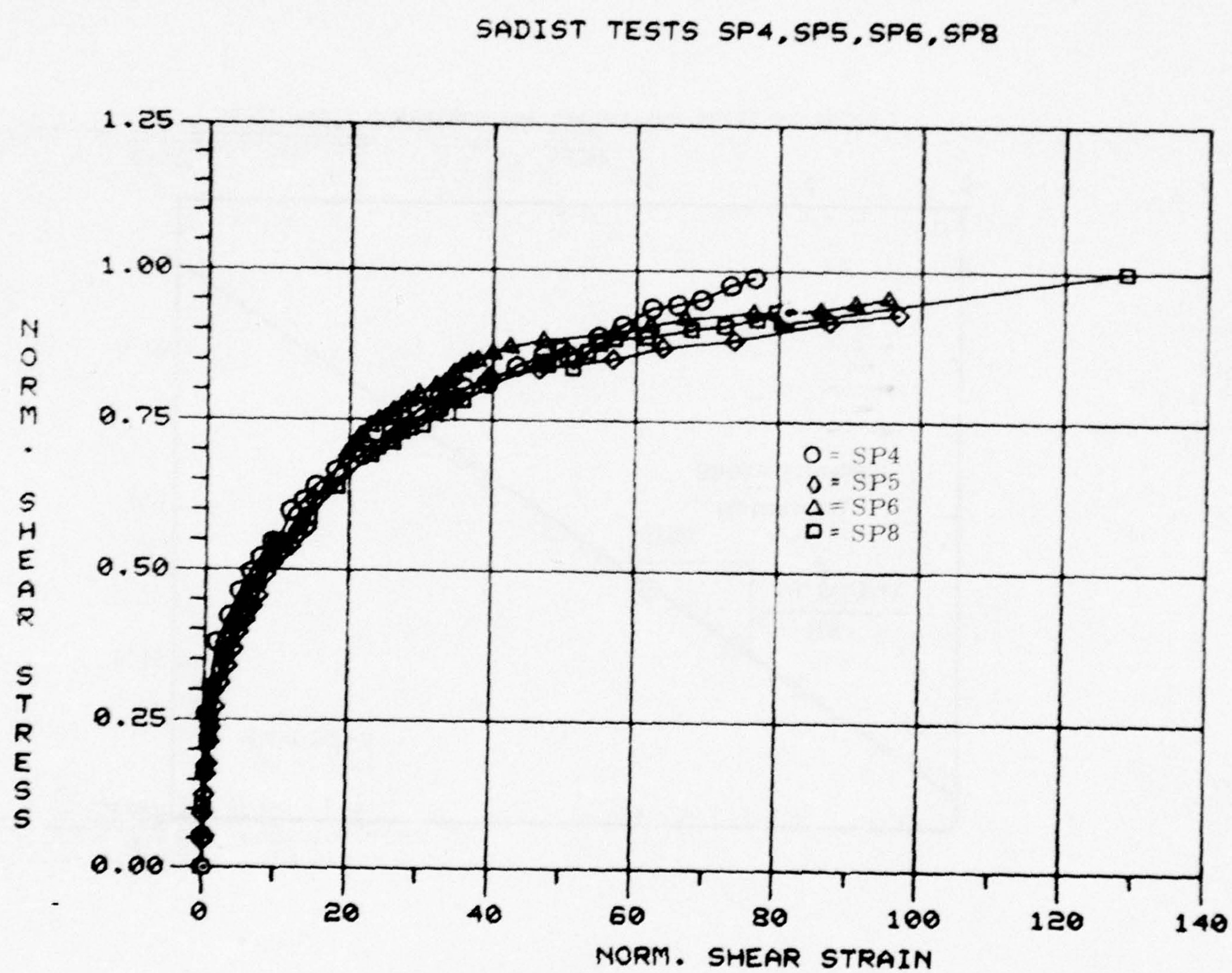


Fig. 41. Remolded Samples SP4, SP5, SP6, SP8
Normalized Shear Stress versus Normalized
Shear Strain

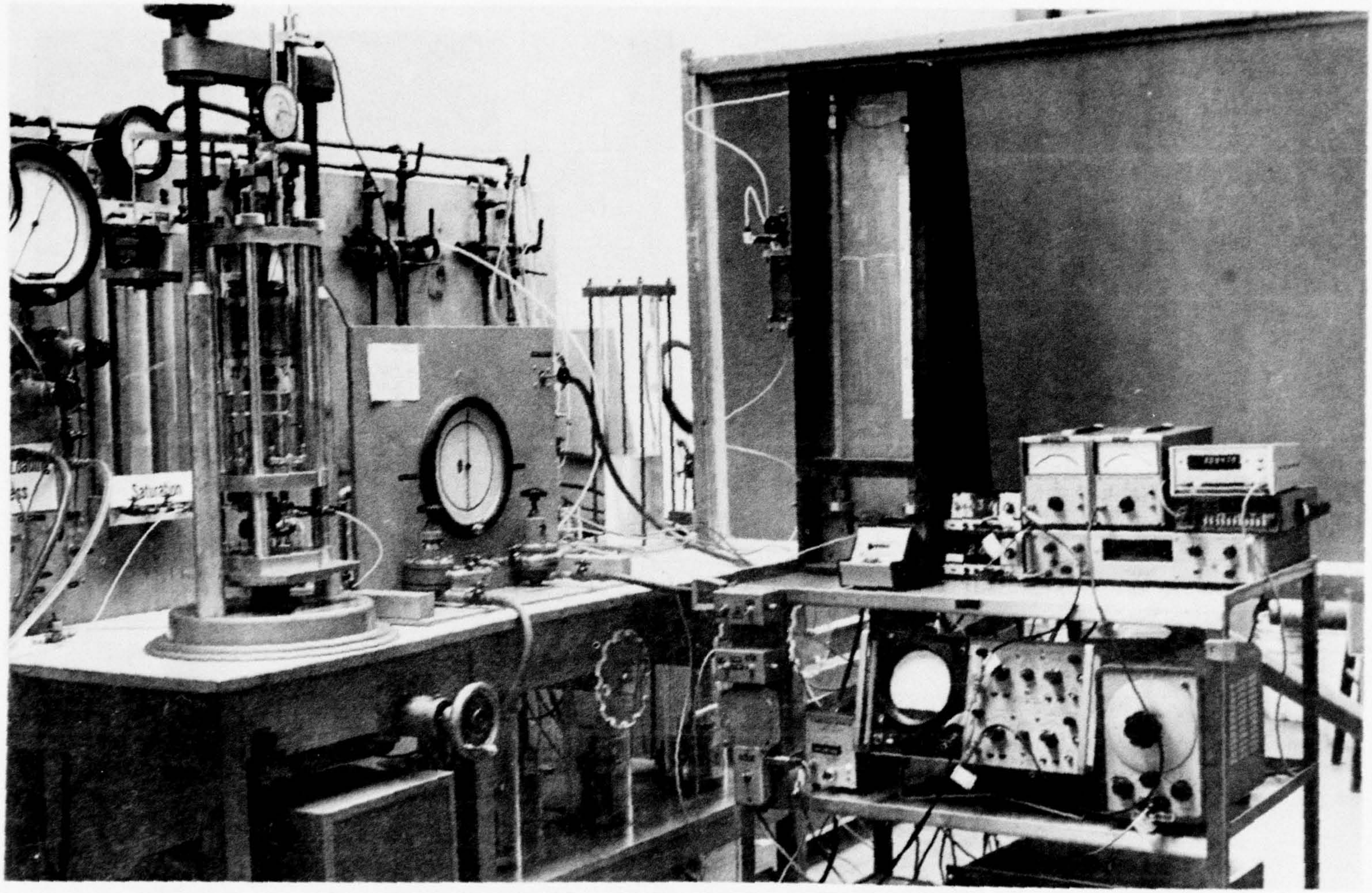


Fig. 42. Overall View of Triaxial/Resonant Column System

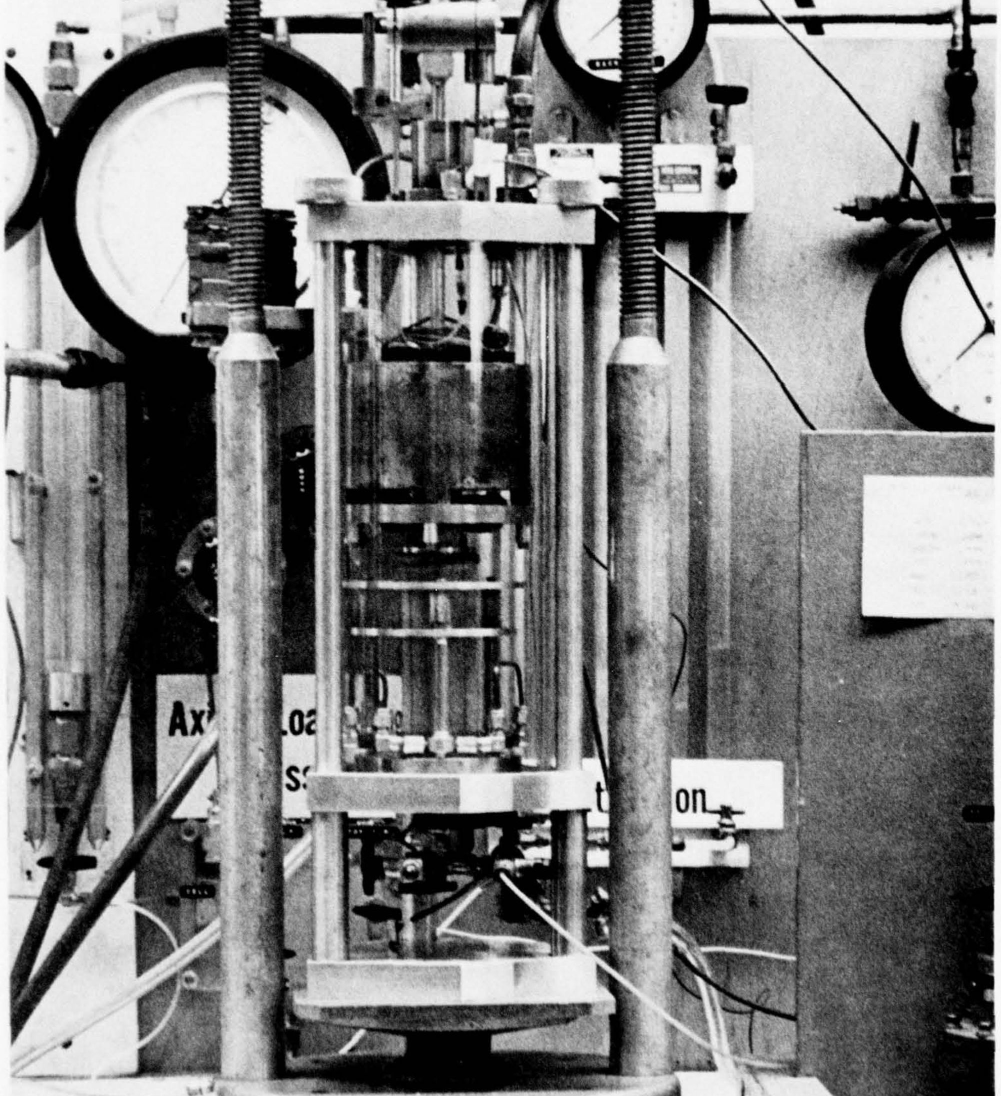


Fig. 43. Triaxial Cell With Hardin Oscillator

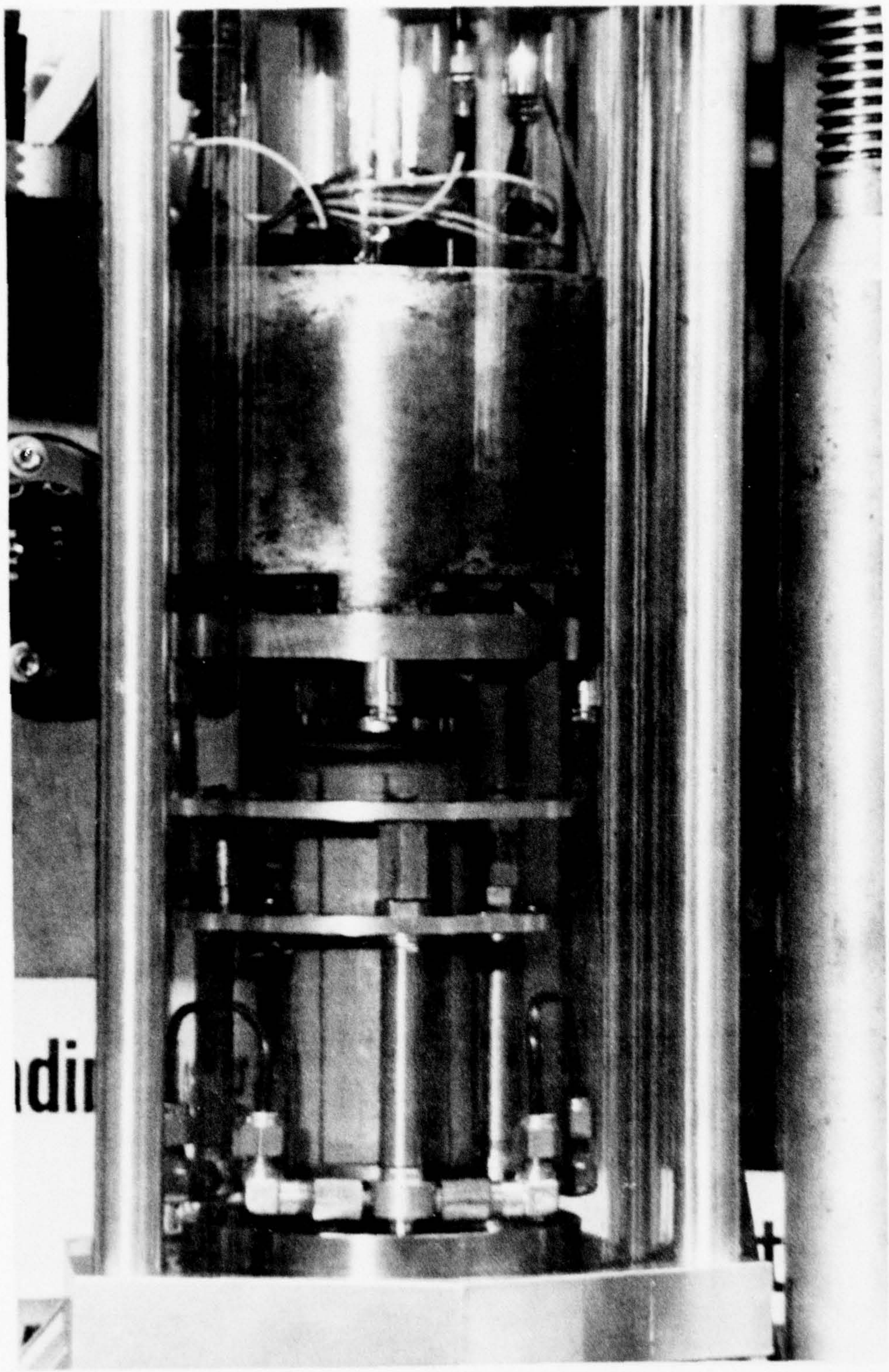


Fig. 44. Close-up View of Hardin Oscillator in Cell

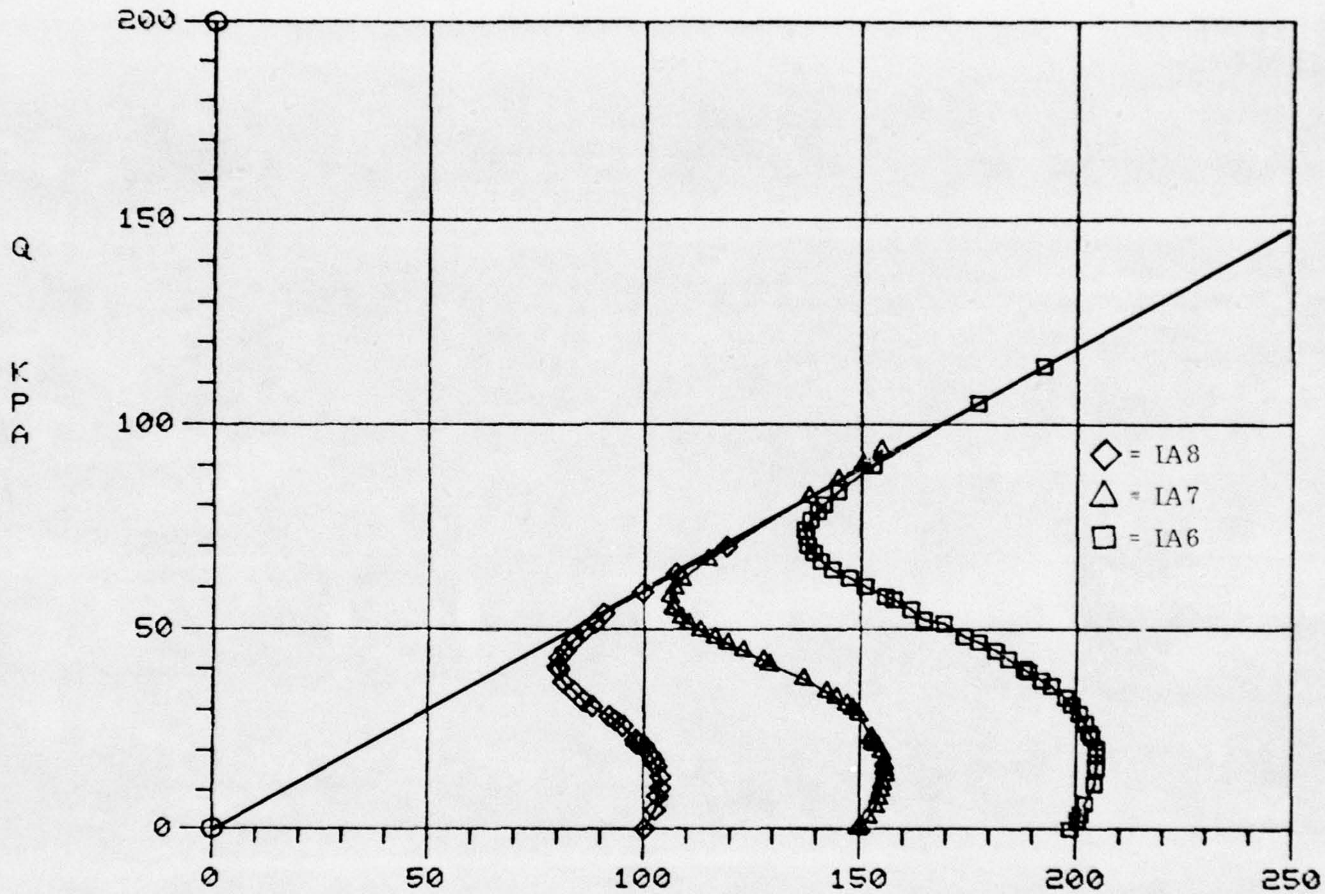


Fig. 45. Triaxial/Resonant Column Stress Paths
Undrained Test

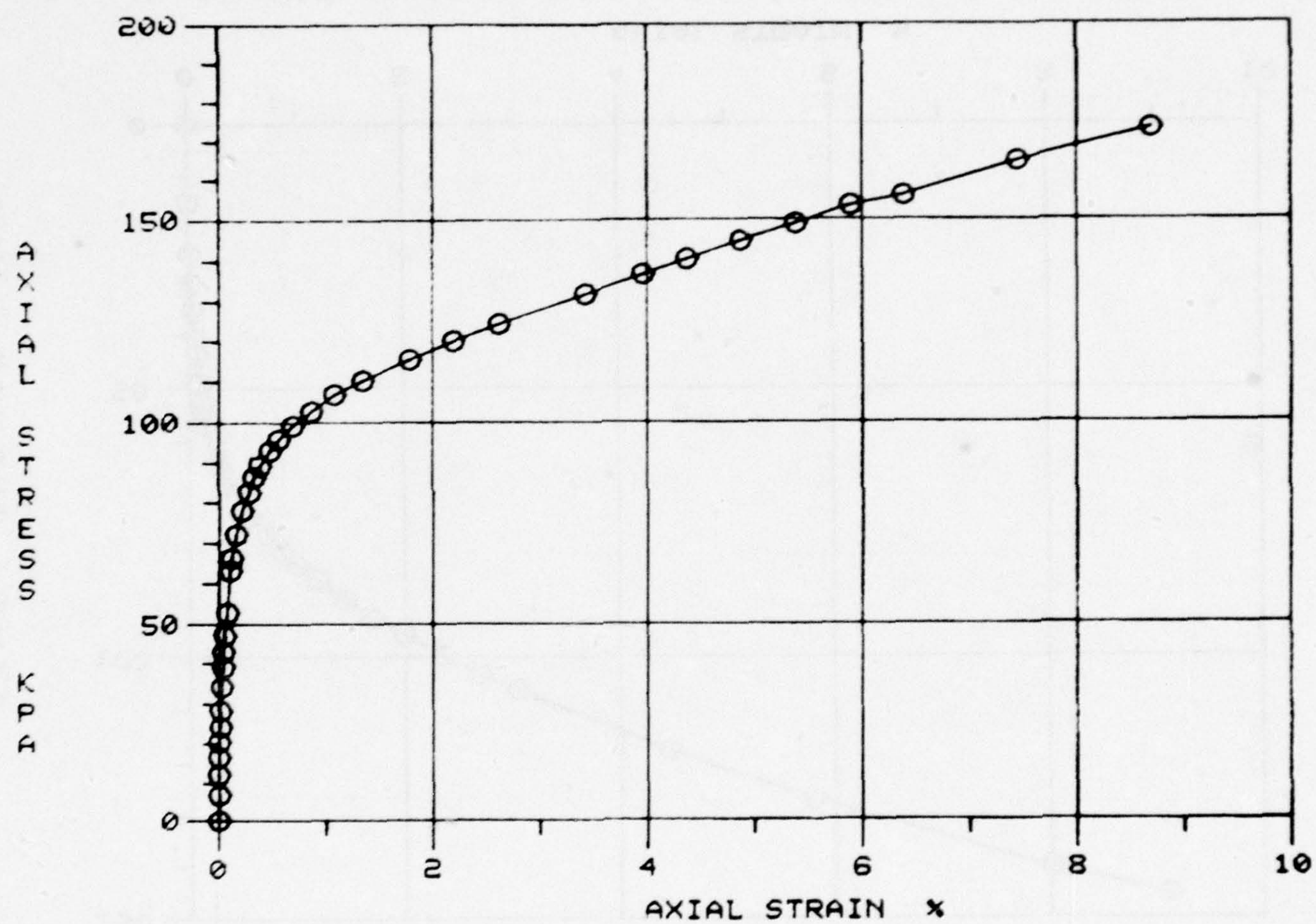


Fig. 46. Triaxial/Resonant Column Undrained Test, Init. Eff. Conf. Stress 150 kPa

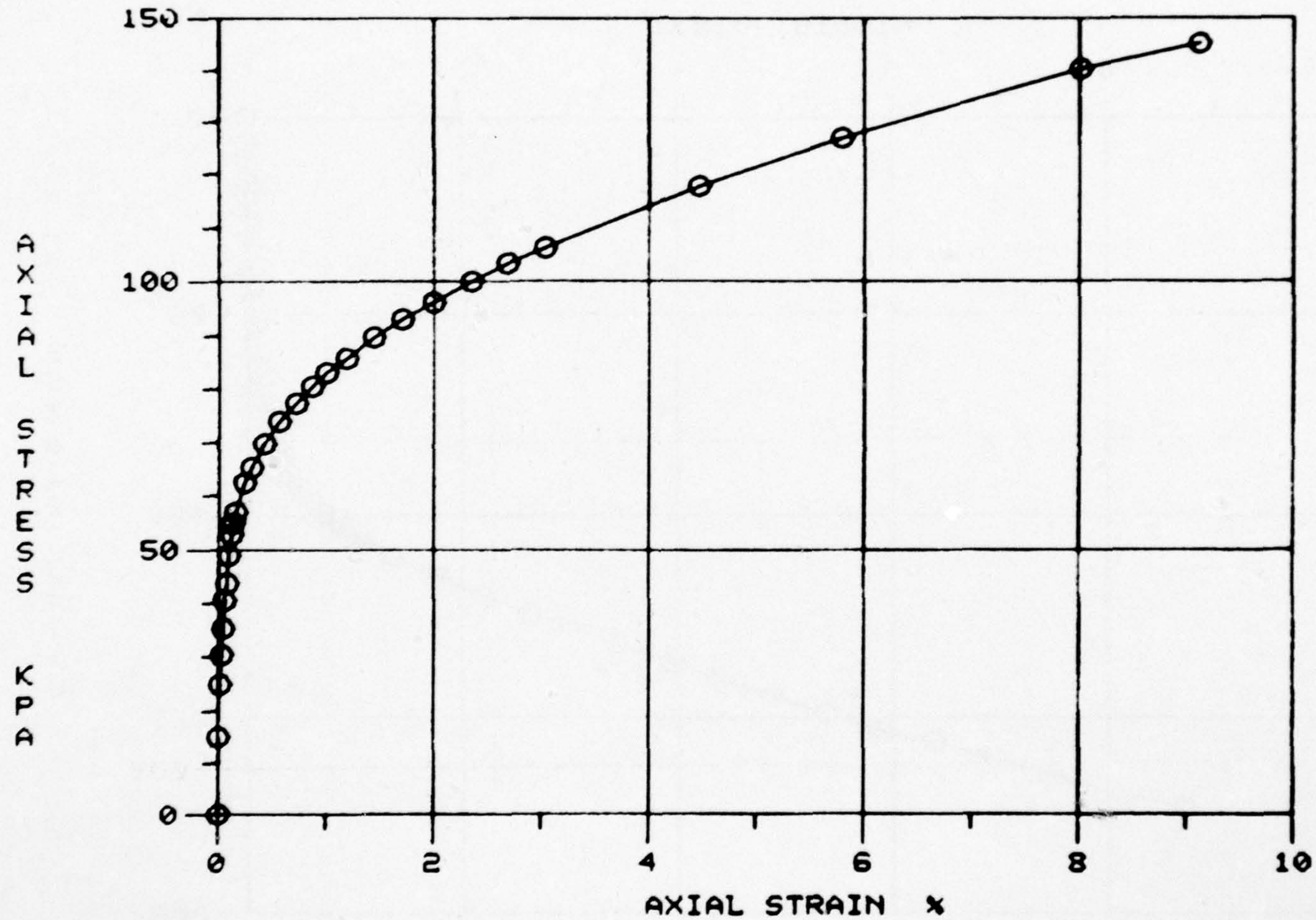


Fig. 47. Triaxial/Resonant Column Undrained Test, Init. Eff. Conf. Stress 100 kPa

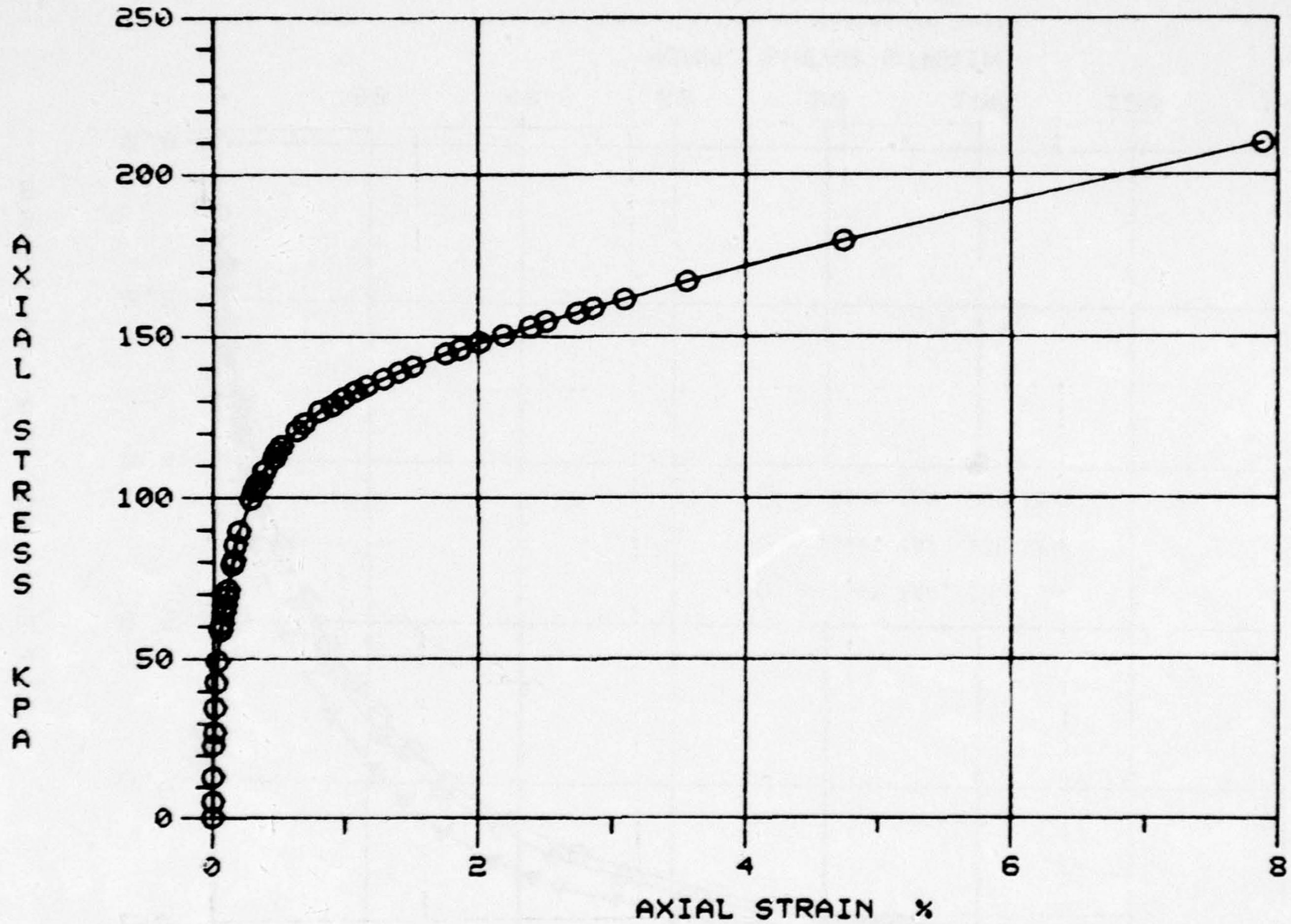


Fig. 48. Triaxial/Resonant Column Undrained Test, Init. Eff. Conf. Stress 200 kPa

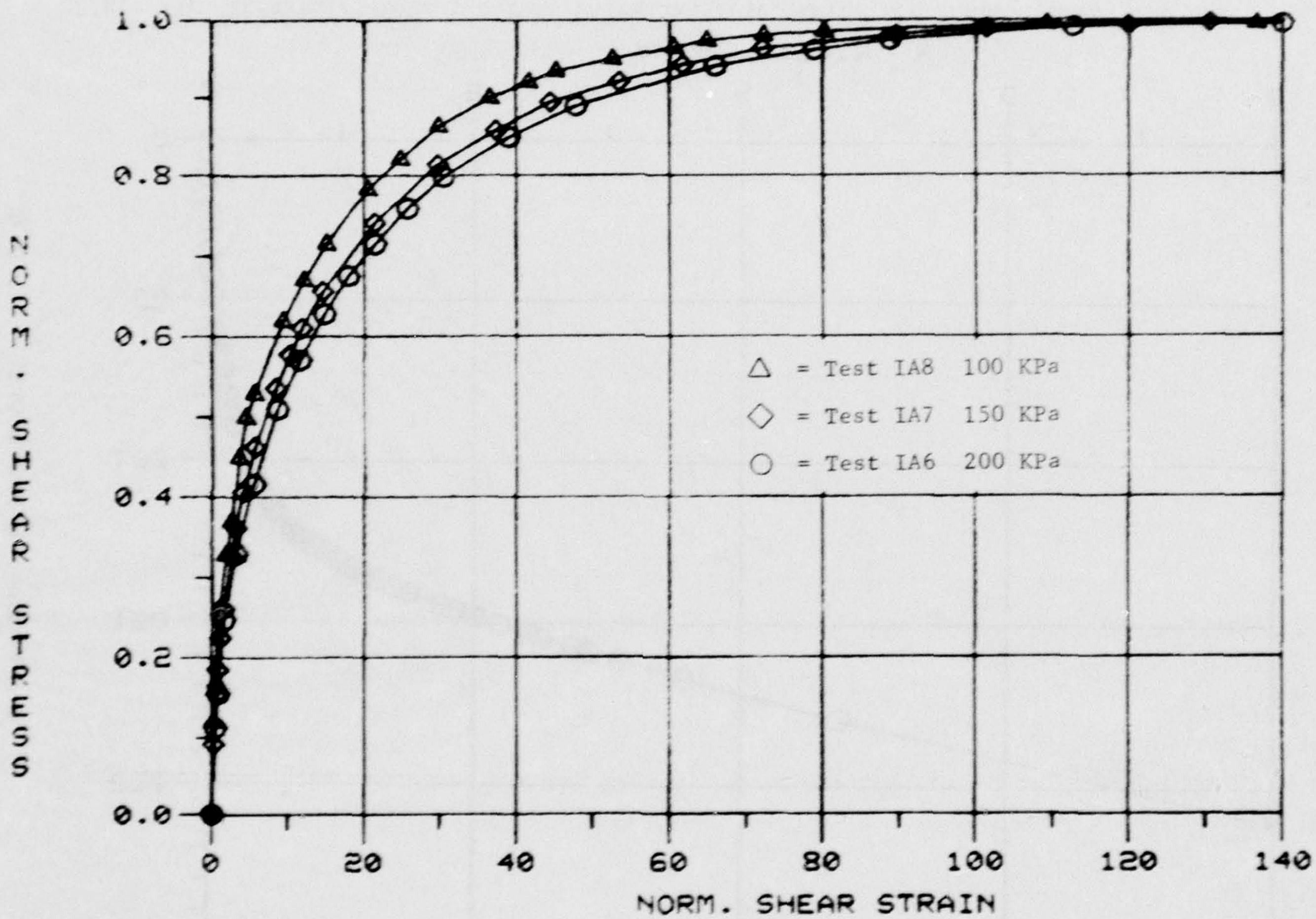


Fig. 49. Triaxial/Resonant Column Undrained Tests
Init. Eff. Conf. Stress 100, 150, 200 kPa

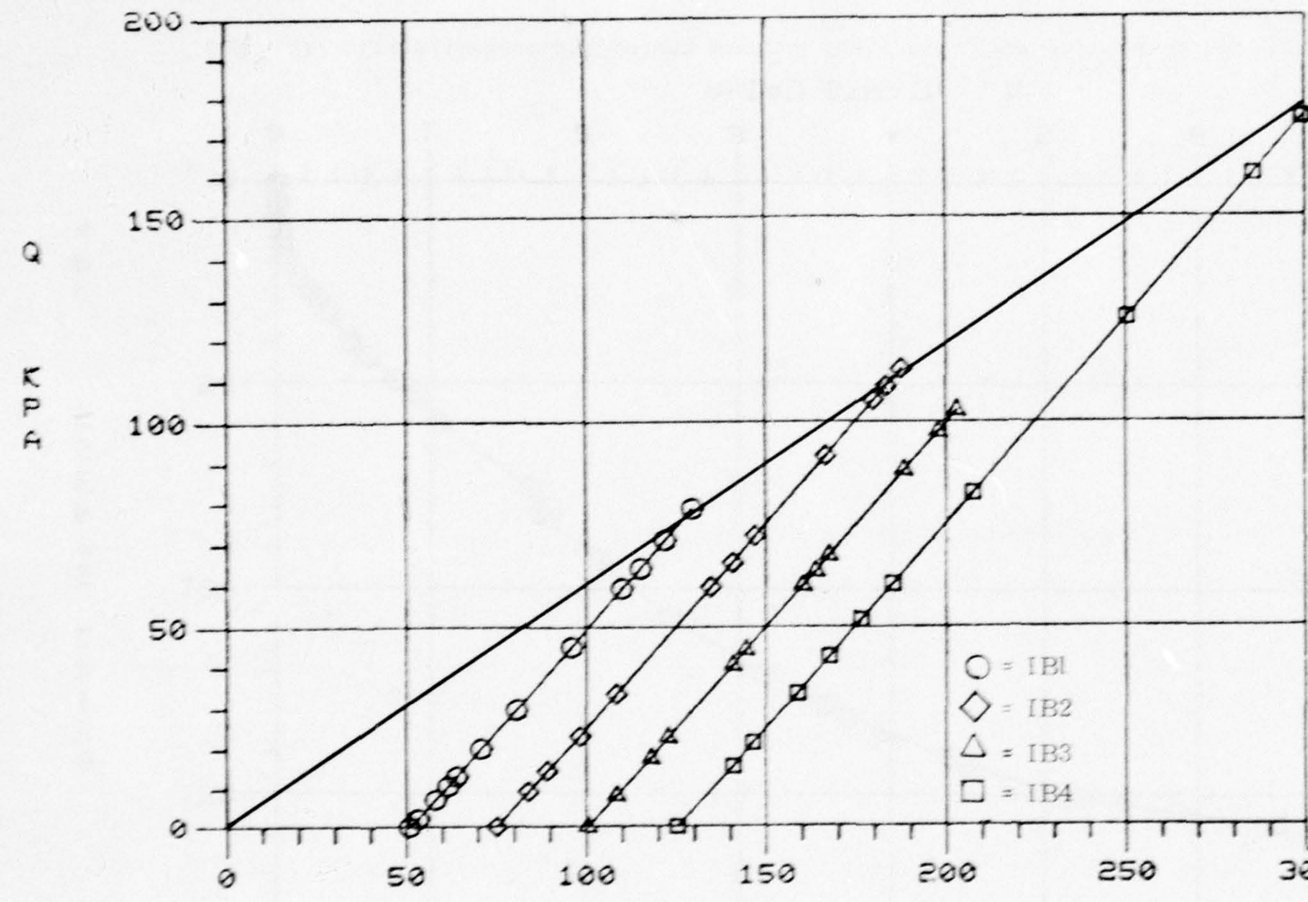


Fig. 50. Triaxial/Resonant Column Stress Paths
Drained Tests

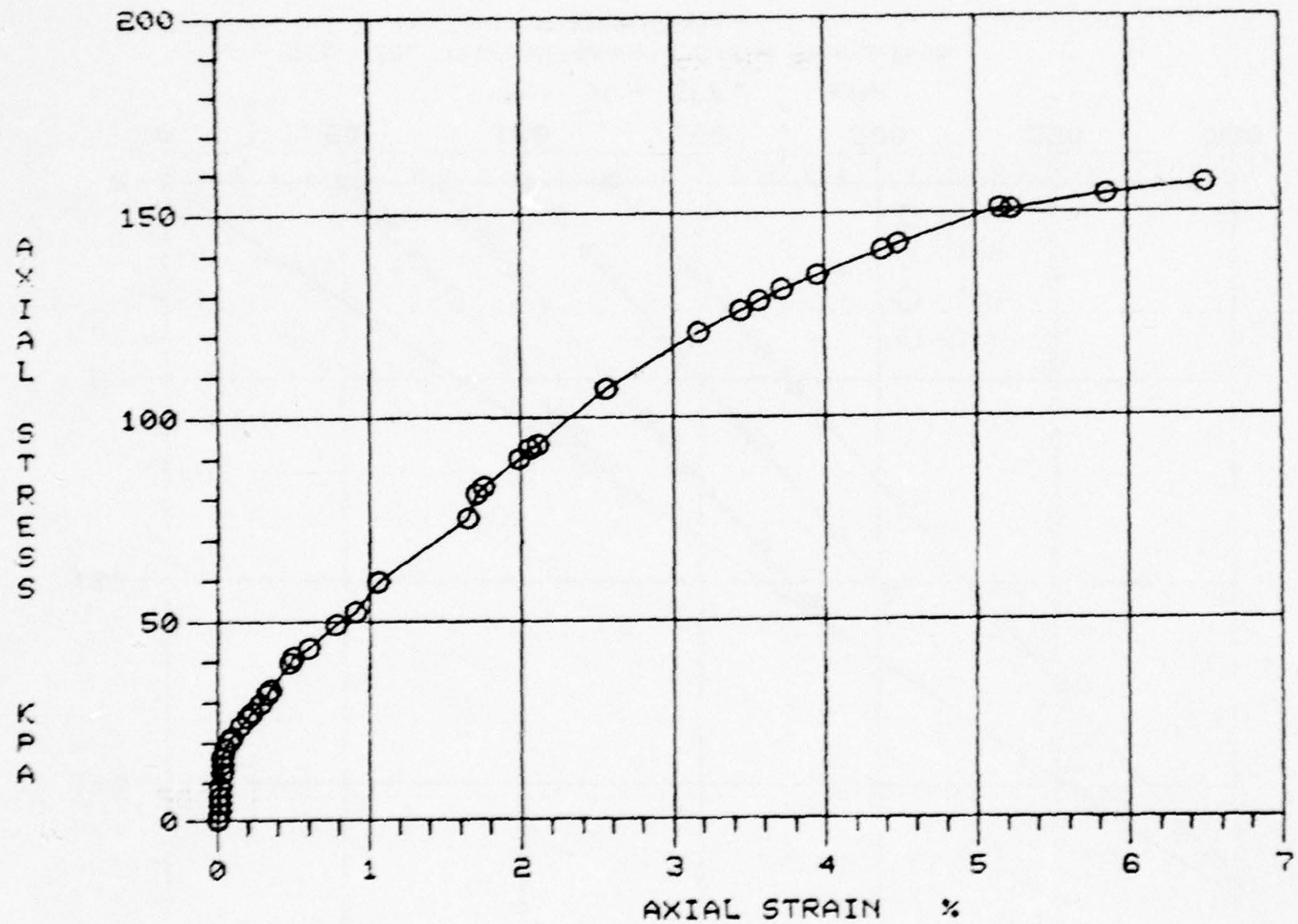


Fig. 51. Triaxial/Resonant Column Drained Test, Eff. Conf. Stress 50 kPa

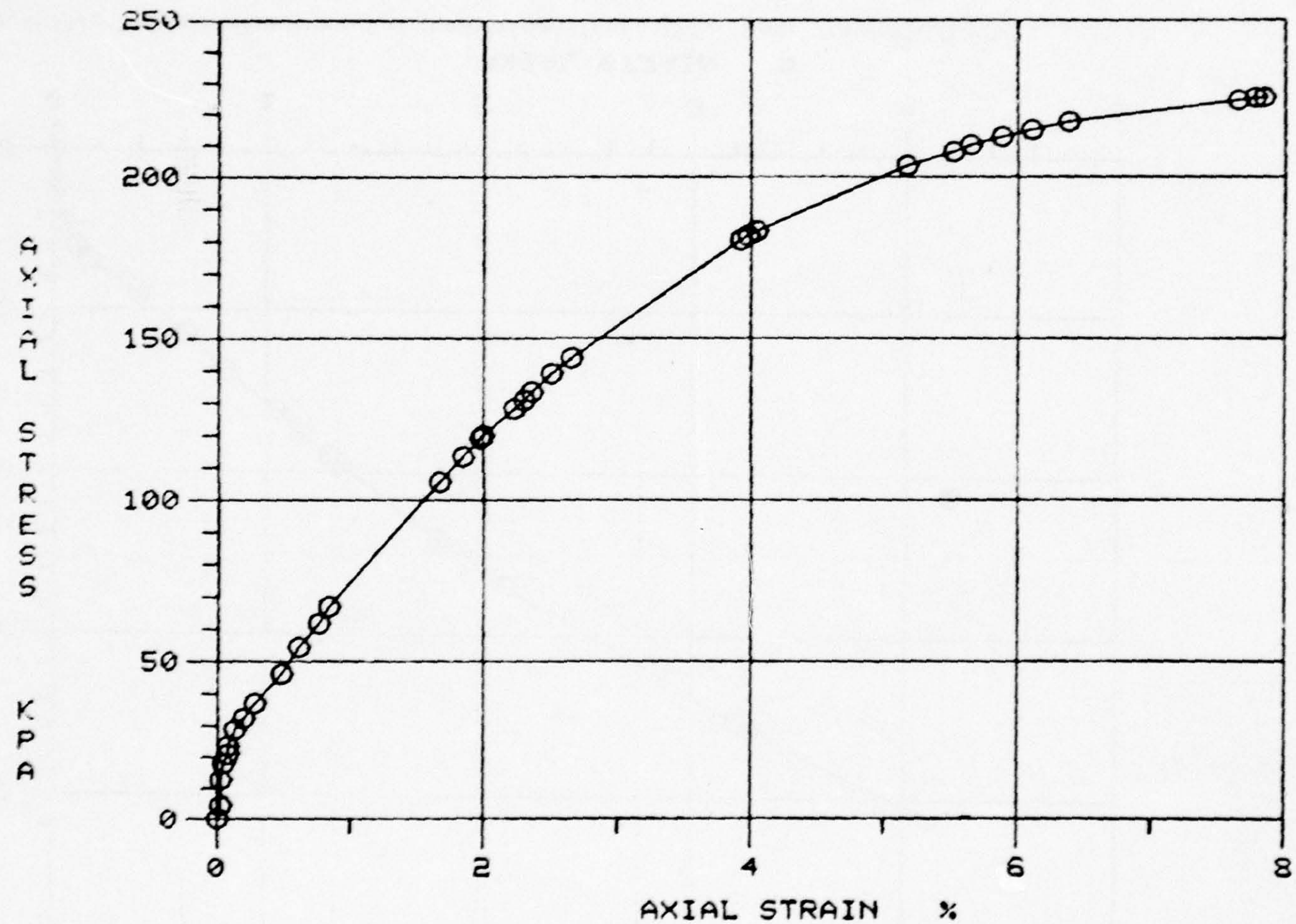


Fig. 52. Triaxial/Resonant Column Drained Test, Eff. Conf. Stress 75 kPa

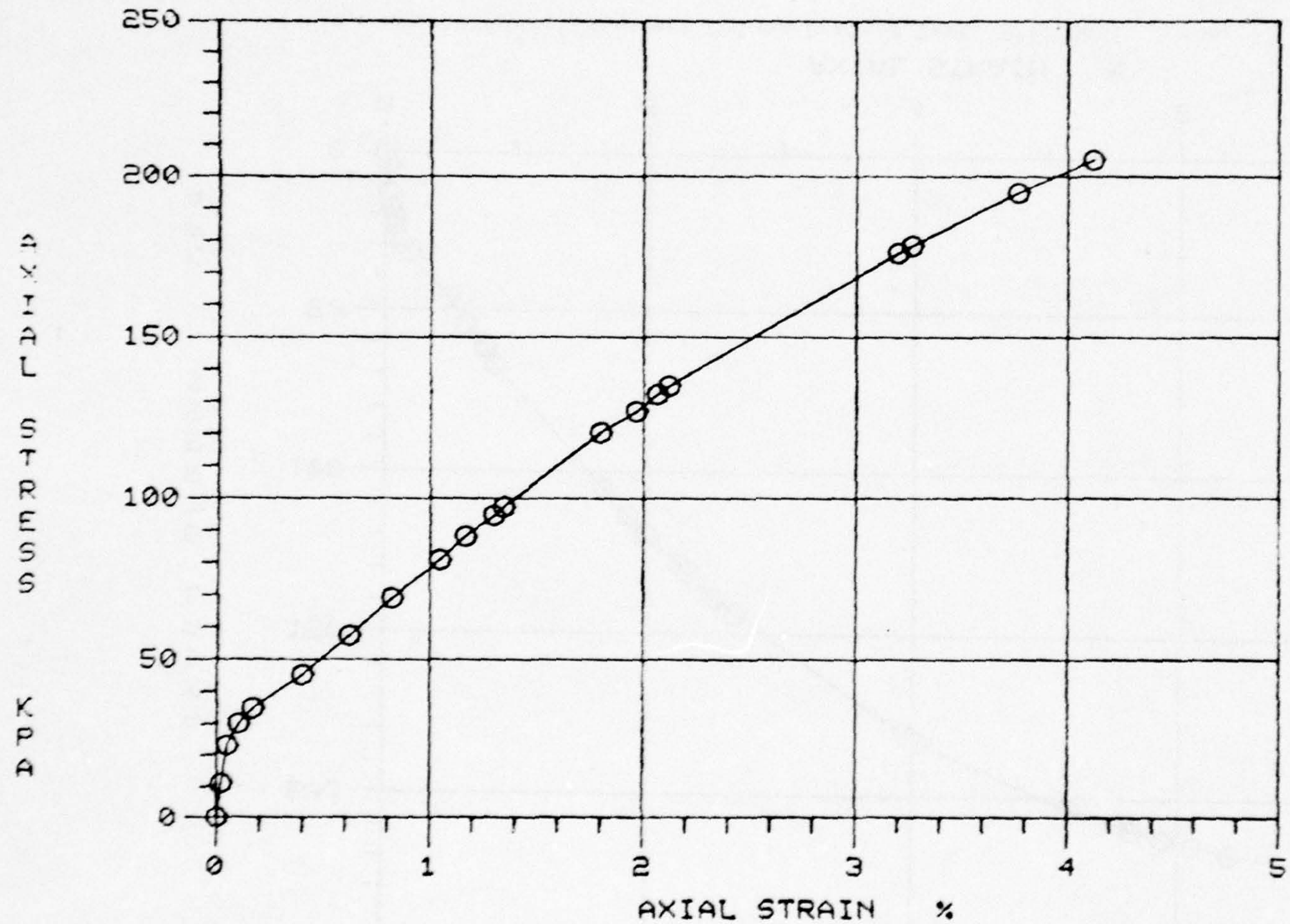


Fig. 53. Triaxial/Resonant Column Drained Test, Eff. Conf. Stress 100 kPa

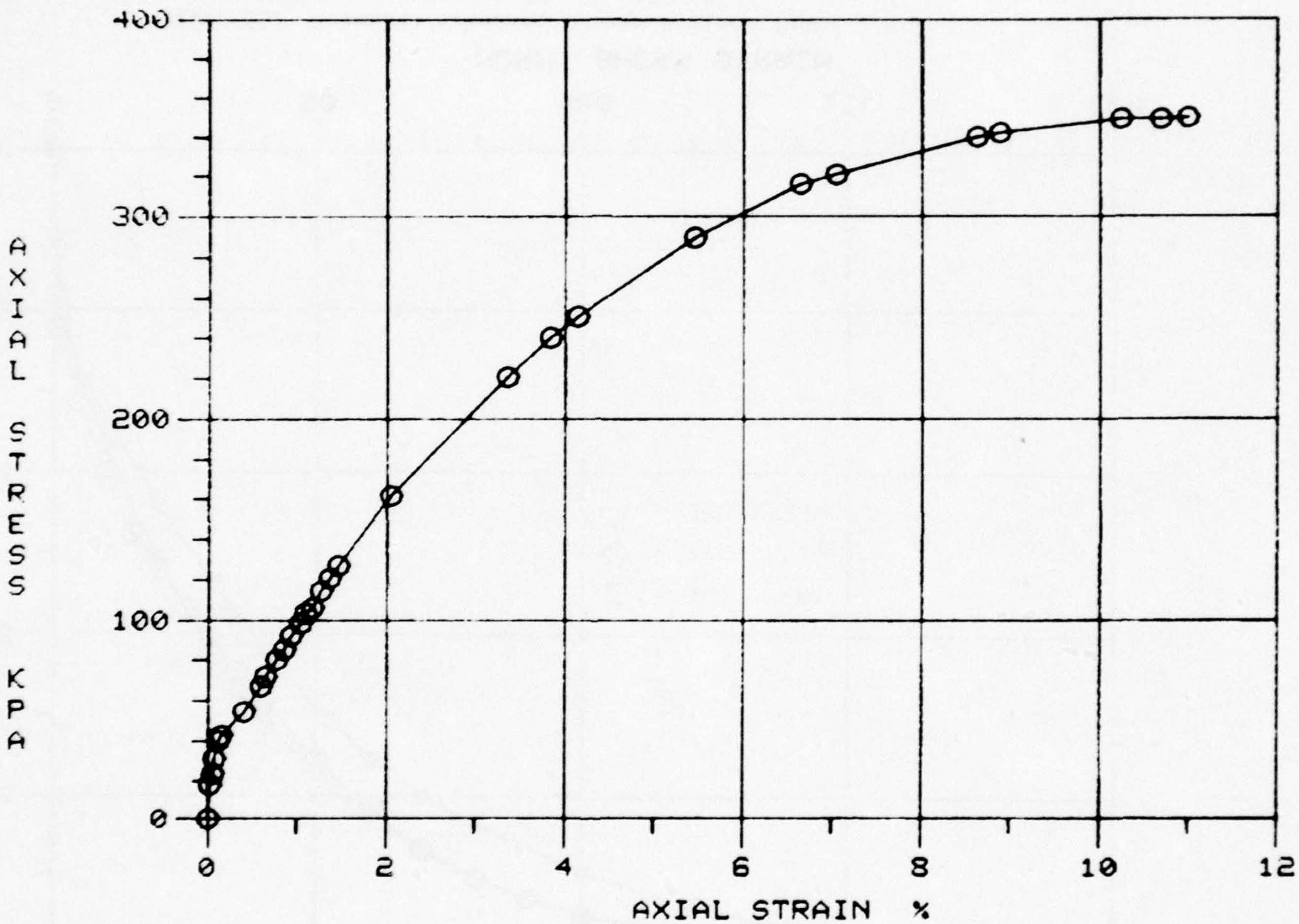


Fig. 54. Triaxial/Resonant Column Drained Test, Eff. Conf. Stress 125 kPa

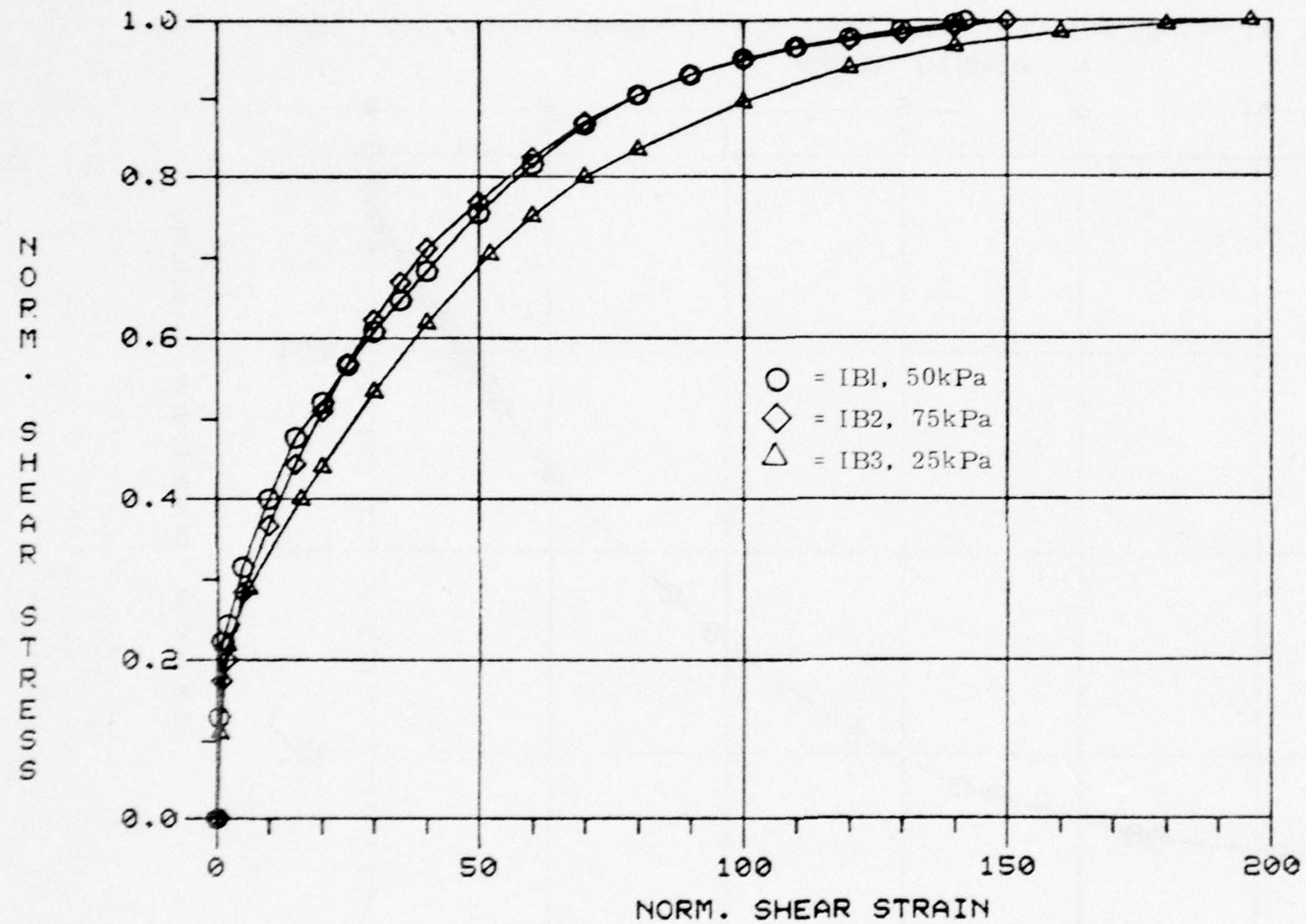


Fig. 55. Triaxial/Resonant Column Drained Tests
Eff. Conf. Stress 50, 75, 125 kPa

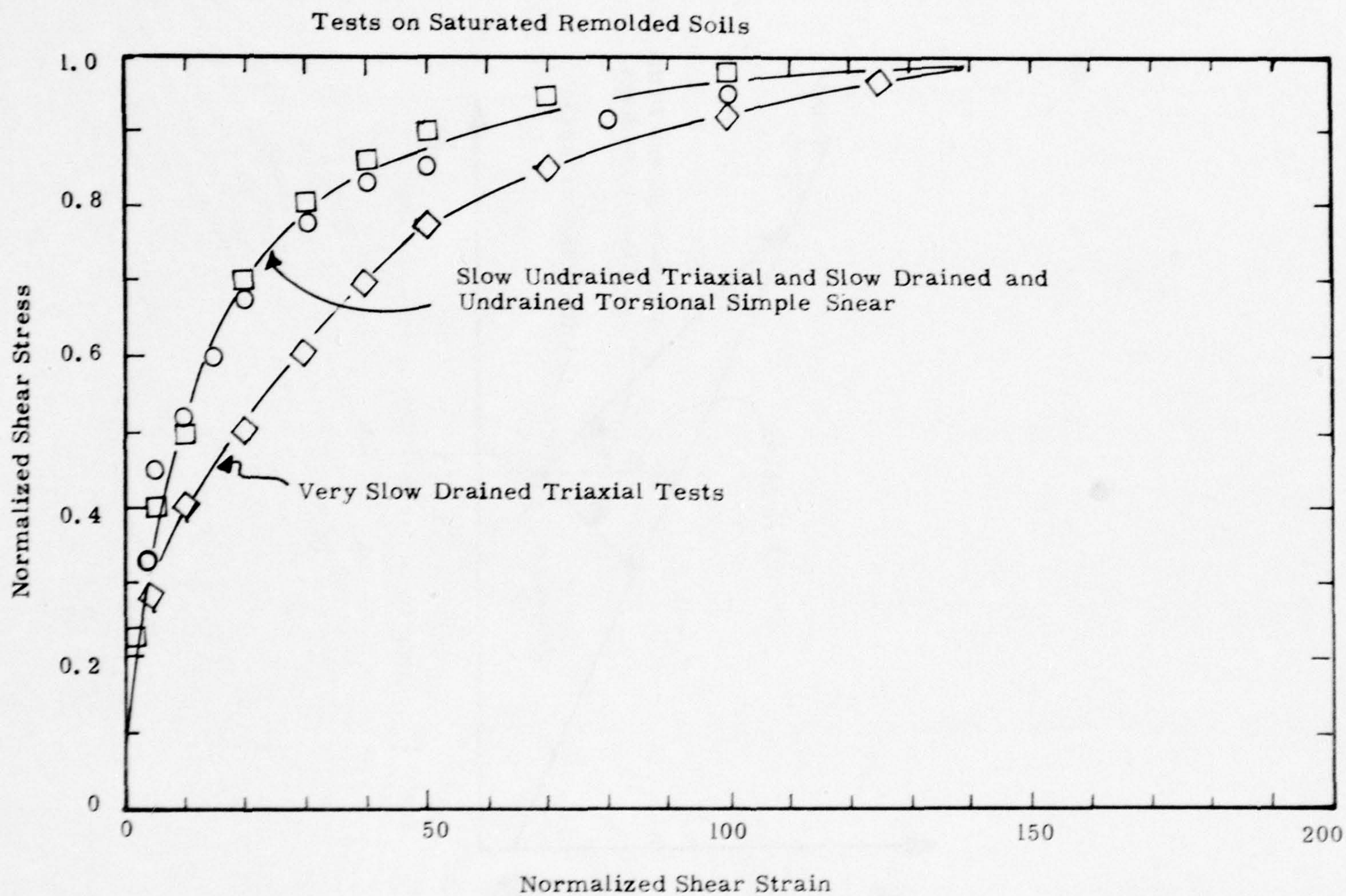


Fig. 56. Comparison of Normalized Data

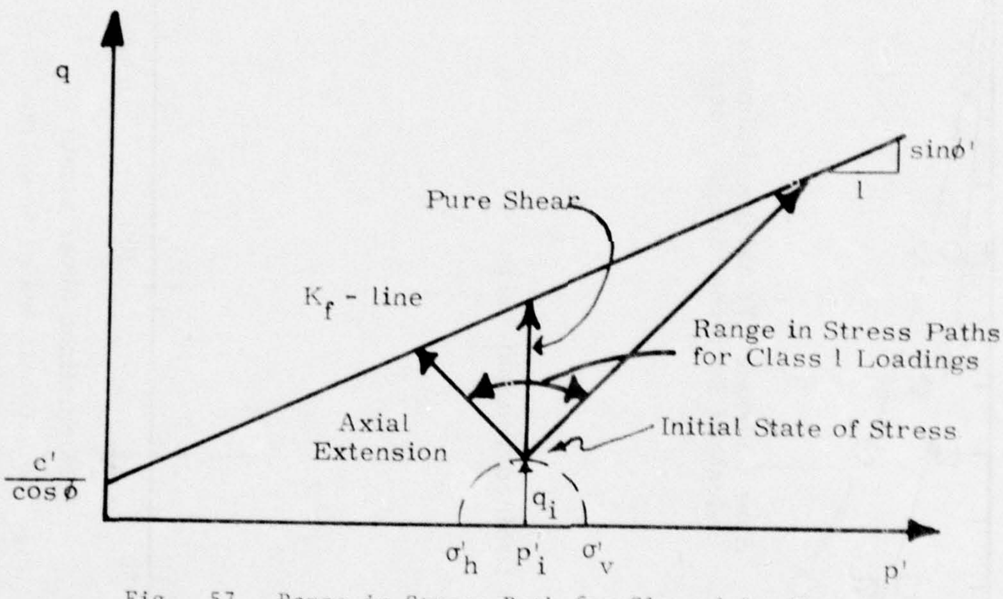


Fig. 57. Range in Stress Path for Class 1 Loadings

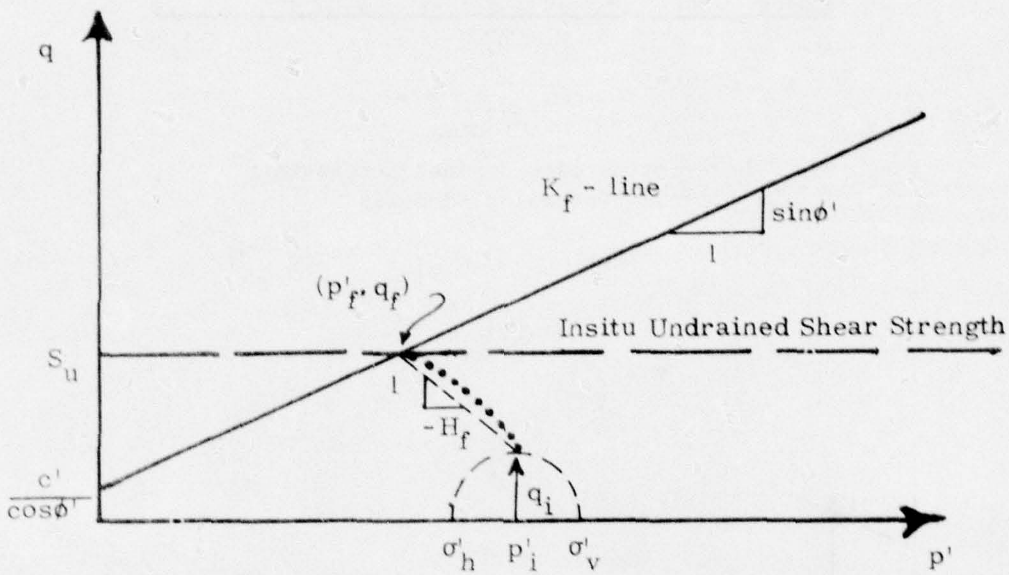


Fig. 58. Effective Stress Paths In Situ for Undrained Conditions

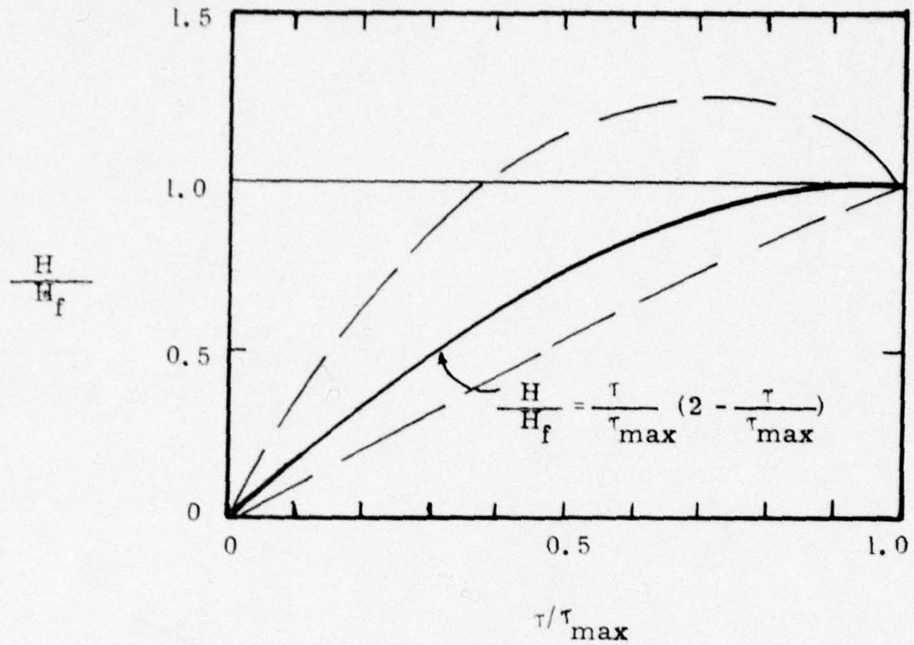


Fig. 59a. Description of Undrained Stress Path for Normally Consolidated Soils

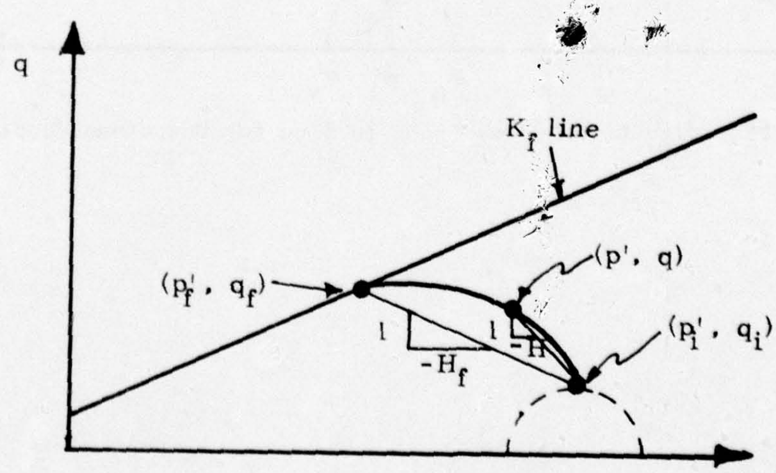


Fig. 59b. Definition of H Stress Path Parameter

APPENDIX A: COMPUTER PROGRAM FOR REDUCING DRNEVICH RESONANT COLUMN DATA

```
C******************         RC5 FORTRAN        ***************************** RC500010
C   DATA REDUCTION PROGRAM FOR DRNEVICH LONG-TOR RESONANT COLUMN APP.    RC500020
C   USING THE EXACT VISCOELASTIC THEORY ACCORDING TO THE PAPER           RC500030
C   BY DRNEVICH, 1978                                                    RC500040
C                                                                        RC500050
C   WRITTEN BY V.P. DRNEVICH                                             RC500060
C                                                                        RC500070
C   MAY 1978 VERSION                                                     RC500080
C                                                                        RC500090
C                                                                        RC500100
C   PARAMETER DEFINITIONS                                                RC500110
C       APPARATUS CONSTANTS                                              RC500120
C         MA   =TOP CAP AND OSCILLATOR(S) MASS (KG)                      RC500130
C         JA   =APPARATUS POLAR MASS INERTIA (KG-M**2)                   RC500140
C         LCFA =LONG. MOTION C.F. FOR LONG. VIB. (M/VRMS)                RC500150
C         RCFA =ROT. MOTION C.F. FOR TORS. VIB. (RAD/VRMS)               RC500160
C         ADCL =APPARATUS DAMPING COEFF. FOR LONG. MOTION (KG-HZ)        RC500170
C         ADCT =APPARATUS DAMPING COEFF. FOR TORS. MOTION (KG-M**2-HZ)   RC500180
C         FCF  =FORCE-CURRENT FACTOR FOR LONGITUDINAL MOTION (N/VRMS)    RC500190
C         TCF  =TORQUE-CURRENT FACTOR FOR TORSIONAL MOTION (N-M/VRMS)    RC500200
C         MODE =TYPE OF VIB. (LONG. OR TORS.)                            RC500210
C         LONG =LONGITUDINAL MOTION (CODE =LONG)                         RC500220
C         TORS =TORSIONAL MOTION (CODE =TORS)                            RC500230
C       GENERAL CONSTANTS                                                RC500240
C         PI   =3.14159                                                  RC500250
C         UWAT =UNIT WEIGHT OF WATER = 1000. (KG/M**3)                   RC500260
C       SPECIMEN VARIABLES                                               RC500270
C         W    =SPECIMEN WEIGHT (GMS)                                    RC500280
C         SD   =SPECIMEN DIAMETER (MM)                                   RC500290
C         SL   =SPECIMEN LENGTH (MM)                                     RC500300
C         SG   =SPECIFIC GRAVITY OF SPECIMEN SOLIDS                      RC500310
C         WC   =WATER CONTENT OF SPECIMEN (PERCENT)                      RC500320
C         UM   =MASS DENSITY OF SPECIMEN (KG/M**3)                       RC500330
C         SJ   =SPECIMEN POLAR INERTIA (M**4)                            RC500340
C         SINR =SPECIMEN MASS POLAR INERTIA (KG-M**2)                    RC500350
C         E    =SPECIMEN VOID RATIO                                      RC500360
C         SAT  =DEGREE OF SATURATION (PERCENT)                           RC500370
C       SYSTEM VARIABLES                                                 RC500380
C         LRI  =INITIAL LENGTH DIAL READING (UNITS)                      RC500390
C         LCF  =LENGTH CHNG. CAL. FACT.(MM/UNIT)(+ FOR LENGTH DECREASE) RC500400
C         LR   =LENGTH READING (UNITS) (COMPRESSION IS POSITIVE)         RC500410
C         BRI  =INITIAL BURETTE READING (UNITS)                          RC500420
C         BCF  =BUR. CAL. FACTOR (ML/UNIT)(+ FOR PORE VOL. INCREASE)     RC500430
C         BR   =BURETTE READING (UNITS) (INCR. FOR PORE VOL. INCR.)      RC500440
C         TTOR =SYSTEM POLAR MASS INERTIA RATIO                          RC500450
C         TLON =SYSTEM MASS INERTIA RATIO                                RC500460
C         TIME =TIME OF VIBRATION (MIN)                                  RC500470
C         CP   =CELL PRESSURE (UNITS)                                    RC500480
C         BP   =BACK PRESSURE OR PORE PRESSURE (UNITS)                   RC500490
C         PCF  =PRESSURE CALIBRATION FACTOR (KPA/UNIT)                   RC500500
C         CRRMS=TORQUE READING (MV-RMS)                                  RC500510
C         TORMS=ACCELEROMETER OUTPUT (MV-RMS)                            RC500520
```

```
C         FSYS =SYSTEM UNDAMPED NATURAL FREQUENCY (HZ)
C       CALCULATED SOIL PARAMETERS
C         V     =VOLUME (M**3)
C         L     =LENGTH (M)
C         AS    =AXIAL STRAIN (PERCENT) (+ FOR COMPRESSION)
C         E,VR =VOID RATIO
C         SS    =AVERAGE SHEAR OR ROD STRAIN AMPLITUDE IN SPECIMEN (%)
C         G     =ROD MODULUS OR SHEAR MODULUS (MPA)
C         DR    =DAMPING RATIO (PERCENT)
C         CYC   =CYCLES OF VIBRATION
C         SO    =MEAN EFFECTIVE PRINCIPLE STRESS (KPA)
C       TEST PARAMETERS
C         TEST =TEST NAME (MAX.=40 ALPHA-NUMERIC CHARACTERS)
C         TESTN=TEST NUMBER (MAX.=16 ALPHA-NUMERIC CHARACTERS)
C         DATE =DATE (MO/DA/YR)
C         SOIL =SOIL TYPE (MAX.=40 ALPHA-NUMERIC CHARACTERS)
C         NDP   =NUMBER OF DATA POINTS IN TEST (MAX.=100)
C         OPER =OPERATOR:S NAME (MAX.=16 ALPHA-NUMERIC CHARACTERS)
C         LCT   =NUMBER OF DATA LINES
C         NP    =NUMBER OF PAGES REQUIRED FOR DATA REDUCTION
C         NSETS =NUMBER OF TIMES PROGRAM IS TO BE RUN (MAX=9)
C
C
      INTEGER NDP,LCT,NP,OD,TORS
      REAL LRI,LCF,LR(100),L(100),OPER,LCFA,MA,JA,MMF
      DIMENSION TEST(10),OPER(4),SOIL(10),TESTN(4),DATE(2)
      DIMENSION TIME(100),CP(100),BP(100),CRRMS(100),TORMS(100)
      DIMENSION MODE(100),BR(100),FSYS(100),AS(100)
      DIMENSION V(100),VR(100),SO(100),CYC(100),SS(100),G(100),DIA(100)
      DIMENSION DR(100),MN(100)
      COMMON /VALS/P,T,ADF,MMF,JPA,AMP,D,F,SF/MAP/MAL/ALARM/KALARM
      DATA LONG/4HLONG/,TORS/4HTORS/
C
C
C     SETTING INPUT AND OUTPUT DEVICE CODES
C
      ID=5
      OD=6
C
    5 FORMAT(10A4,10A4)
   10 FORMAT(2A4,4A4,4A4)
   15 FORMAT(8F8.0)
   20 FORMAT(F8.2,3F8.3,F8.2)
   25 FORMAT(2F8.2,F8.4)
   30 FORMAT(F8.3,F8.2,I3)
   40 FORMAT(4F8.2,F8.3,A4,3F8.2)
   50 FORMAT(1H1,5X,61HDRNEVICH LONGITUDINAL AND TORSIONAL RESONANT COLU
     1MN APPARATUS/15X,37HPROGRAMMED BY DR. VINCENT P. DRNEVICH/22X,22HP
     2ROGRAM DATE MAY, 1978///18X,30HRESONANT COLUMN DATA REDUCTION)
   55 FORMAT(1H ,2X,11HTEST NAME: ,10A4/3X,18HSOIL DESCRIPTION: ,10A4///
     12X,12H TEST DATE: ,2A4,11X,26H TEST NAME AND/OR NUMBER: ,4A4/2X,11
     2H OPERATOR: ,4A4///)
   65 FORMAT(1H ,3X,30H APPARATUS CALIBRATION FACTORS,12X,23H SYSTEM CHA
     1RACTERISTICS//)
```

```
   70 FORMAT(1H ,1X,11HMA          =,F7.5,1X,37HKILOGRAMS                  LENGTH RC501070
     1CHNG. C.F.=,F7.3,1X,7HM/UNIT )                                             RC501080
   75 FORMAT(1H ,1X,11HLCFA*F**2 =,F7.5,1X,37H(M/VRMS)*(HZ)**2         INIT. LRC501090
     1ENGTH RDG.=,F7.3,1X,8HUNITS    )                                           RC501100
   80 FORMAT(1H ,1X,11HADCL        =,F7.5,1X,37HKG-HZ                      BUR. C.RC501110
     1F.         =,F7.3,1X,8HML/UNIT )                                           RC501120
   85 FORMAT(1H ,1X,11HFCF         =,F7.4,1X,37HN/VRMS                     INIT. BRC501130
     1UR. RDG.  =,F7.2,1X,8HUNITS    )                                           RC501140
   90 FORMAT(1H ,1X,11HJA          =,F7.5,1X,37HKG-M**2                    PRESS. RC501150
     1C.F.       =,F7.3,1X,8HKPA/UNIT)                                           RC501160
   92 FORMAT(1H ,1X,11HRCFA*F**2 =,F7.5,1X,37H(RAD/VRMS)*(HZ)**2 LONGITURC501170
     1DINAL T    =,F7.2)                                                         RC501180
   94 FORMAT(1H ,1X,11HADCT        =,F7.5,1X,37HKG-M**2-HZ                 TORSIONRC501190
     1AL T       =,F7.2)                                                         RC501200
   96 FORMAT(1H ,1X,11HTCF         =,F7.4,1X,37HN-M/VRMS                   NO. OF RC501210
     1DATA PTS. =,4X,I3//)                                                       RC501220
  100 FORMAT(1H ,23X,24HSPECIMEN CHARACTERISTICS//)                              RC501230
  102 FORMAT(1H ,1X,16HMASS              =,F7.5,1X,32HKG              DEGREE OFRC501240
     1 SAT.      =,F6.2,2H %)                                                    RC501250
  103 FORMAT(1H ,1X,16HDIAMETER          =,F7.5,1X,29HM               MASS DENSRC501260
     1ITY     =,F10.1,1X,7HKG/M**3)                                              RC501270
  104 FORMAT(1H ,1X,16HLENGTH            =,F7.5,1X,32HM               VOID RATIRC501280
     1O          =,F6.3)                                                         RC501290
  106 FORMAT(1H ,1X,16HSPECIFIC GRAV. =,F5.3,15X,20HROTATIONAL INERTIA =RC501300
     1)                                                                          RC501310
  108 FORMAT(1H ,1X,16HWATER CONTENT  =,F6.2,2X,1H%,28X,F10.7,1X,6HK-M**RC501320
     12)                                                                         RC501330
  110 FORMAT(1H0,1X,11HINPUT DATA://12X,60H    CELL     BACK     BUR.  LENRC501340
     1GTH  LONG.   CUR.  ACCEL.  RES./7X,66HTIME    PRESS.  PRESS.    RDGRC501350
     2.     RDG.  OR     RDG.   RDG.  FREQ./1X,71HLINE  (MIN) (UNITS) (RC501360
     3UNITS) (UNITS)  (UNITS) TORS.(MV-RMS)(MV-RMS) (HZ))                        RC501370
  120 FORMAT(1H ,I3,1X,F7.2,1X,F7.2,1X,F7.2,1X,F7.2,1X,F8.3,1X,A4,1X,     RC501380
     1F7.2,1X,F7.2,1X,F7.2)                                                      RC501390
  130 FORMAT(1H0,1X,16HCALCULATED DATA://14X,55H AX.        EFF.  LONG. RC501400
     1CYCLES       DYN.    DYN. DAMP. /7X,63HTIME     STR. VOID  CONF.  ORRC501410
     2     OF        STR.    MOD. RATIO  /1X,67HLINE   (MIN)    (%)  RATIORC501420
     3 (KPA) TORS.  VIB.          (%)    (MPA)    (%))                           RC501430
  140 FORMAT(1H ,I3,1X,F7.2,1X,F6.3,1X,F5.3,1X,F5.1,1X,A4,1X,F8.0,1X,     RC501440
     1F8.5,1X,F7.2,1X,F5.2)                                                      RC501450
C                                                                                RC501460
C   TEST IDENTIFICATION INPUT                                                    RC501470
C                                                                                RC501480
    1 READ(ID,5,END=999) (TEST(I),I=1,10),(SOIL(I),I=1,10)                       RC501490
    6 READ(ID,10) DATE(1),DATE(2),(TESTN(I),I=1,4),(OPER(I),I=1,4)               RC501500
C                                                                                RC501510
C   APPARATUS CALIBRATION FACTOR INPUT                                           RC501520
C                                                                                RC501530
      READ(ID,15)MA,LCFA,ADCL,FCF,JA,RCFA,ADCT,TCF                               RC501540
C                                                                                RC501550
C   SYSTEM CALIBRATION FACTOR INPUT                                              RC501560
C                                                                                RC501570
      READ(ID,25)LCF,BCF,PCF                                                     RC501580
C                                                                                RC501590
C   SPECIMEN PARAMETER INPUT                                                     RC501600
```

```
C
      READ(ID,20)W,SD,SL,SG,WC
C
C    INITIAL BURETTE, LENGTH READING, AND NUMBER OF DATA SETS INPUT
C
      READ(ID,30)BRI,LRI,NDP
C
C    TEST DATA INPUT
C
      READ(ID,40)(TIME(I),CP(I),BP(I),BR(I),LR(I),MODE(I),CRRMS(I),TORMS
     1(I),FSYS(I),I=1,NDP)
      LCT=0
      NP=1
C
C    WRITE TITLES
C
      WRITE(OD,50)
      WRITE(OD,55)(TEST(I),I=1,10),(SOIL(I),I=1,10),DATE(1),DATE(2),(TES
     1TN(I),I=1,4),(OPER(I),I=1,4)
C
C   CALCULATION OF SPECIMEN CHARACTERISTICS
C
      PI=3.14159
      SL=SL/1000.
      SD=SD/1000.
      LCF=LCF/1000
      W=W/1000.
      VOL=0.25*(SD**2)*PI*SL
      UM=W/VOL
      WSOL=W/(1.+0.01*WC)
      UWAT=1000.
      VSOL=WSOL/(SG*UWAT)
      E=(VOL-VSOL)/VSOL
      WWAT=W-WSOL
      VWAT=WWAT/UWAT
      SAT=VWAT/(VOL-VSOL)*100.
      SINR=W*(SD**2)/8.
      TLON=MA/W
      TTOR=JA/SINR
C
C   WRITE APPARATUS, SYSTEM, AND SPECIMEN CHARACTERISTICS - WITH HEADINGS
C
      WRITE(OD,65)
      WRITE(OD,70)MA,LCF
      WRITE(OD,75)LCFA,LRI
      WRITE(OD,80)ADCL,BCF
      WRITE(OD,85)FCF,BRI
      WRITE(OD,90)JA,PCF
      WRITE(OD,92)RCFA,TLON
      WRITE(OD,94)ADCT,TTOR
      WRITE(OD,96)TCF,NDP
      WRITE(OD,100)
      WRITE(OD,102)W,SAT
      WRITE(OD,103)SD,UM
```

```
      WRITE(OD,104)SL,E
      WRITE(OD,106)SG
      WRITE(OD,108)WC,SINR
C
C   WRITE HEADINGS FOR INPUT DATA
C
  200 CONTINUE
   45 WRITE(OD,50)
      WRITE(OD,55)(TEST(I),I=1,10),(SOIL(I),I=1,10),DATE(1),DATE(2),(TES
     1T(I),I=1,4),(OPER(I),I=1,4)
      WRITE(OD,110)
C
C   WRITE INPUT DATA
C
      IF(NP.EQ.1) ISTART=1
      IF(NP.GT.1) ISTART=LCT+1
      IF(NP.EQ.1) ISTOP=15
      IF(NP.GT.1) ISTOP=15*NP
      IF(ISTOP.GT.NDP) ISTOP=NDP
      DO 250 I=ISTART,ISTOP
      LCT=I
      WRITE(OD,120)LCT,TIME(I),CP(I),BP(I),BR(I),LR(I),MODE(I),CRRMS(I),
     1TORMS(I),FSYS(I)
  250 CONTINUE
C
C   WRITE TITLES FOR CALCULATED DATA
C
      WRITE(OD,130)
C
C   CALCULATION OF INSTANTANEOUS VALUES OF LENGTH,AXIAL STRAIN,VOLUME,
C   VOID RATIO,EFFECTIVE CONFINING PRESSURE, AND CYCLES OF VIBRATION
C
      DO 300 I=ISTART,ISTOP
      L(I)=SL-(LR(I)-LRI)*LCF
      AS(I)=((SL-L(I))/SL)*100.
      DVOL=(BRI-BR(I))*BCF/10.**6
      IF(DVOL.EQ.0.) DVOL=AS(I)*3.*VOL/100.
      V(I)=VOL-DVOL
      VR(I)=E-((VOL-V(I))/VSOL)
      SO(I)=(CP(I)-BP(I))*PCF
      IF(I.NE.1) GO TO 280
      DTIME=TIME(1)
      GO TO 290
  280 DTIME=TIME(I)-TIME(I-1)
  290 CYC(I)=FSYS(I)*DTIME*60.
  300 CONTINUE
C
C   CALCULATION OF DIMENSIONLESS FREQUENCY, MODULUS, DAMPING, MODE
C   SHAPE FACTOR, AND STRAIN AMPLITUDE
C
      JPA=0
      P=10000.
      DO 400 I=ISTART,ISTOP
      IF(FSYS(I).LE.1.) GO TO 400
```

```
      DIA(I)=SQRT(4.*V(I)/(L(I)*PI))
      WT=W-(BRI-BR(I))*BCF/10.**6
      RHO=WT/V(I)
      IF(MODE(I).EQ.LONG) GO TO 310
      GO TO 320
  310 T=MA/WT
      ADF=ADCL/(2.*PI*FSYS(I)*WT)
      MMF=(LCFA*TORMS(I)/(FCF*CRRMS(I)))*WT*(2.*PI)**2
      CALL RCSUB
      IF(MAL.NE.0.OR.KALARM.NE.0)GO TO 400
      G(I)=((RHO*(2.*PI*L(I))**2)*(FSYS(I)/F)**2)/10.**6
      DR(I)=D
      SS(I)=(LCFA/(FSYS(I)**2))*TORMS(I)*(SF/L(I))/10.
         GO TO 400
  320 SINR=WT*DIA(I)*DIA(I)/8.
      T=JA/SINR
      ADF=ADCT/(2.*PI*FSYS(I)*SINR)
      MMF=(RCFA*TORMS(I)/(TCF*CRRMS(I)))*SINR*(2.*PI)**2
      CALL RCSUB
      IF(MAL.NE.0.OR.KALARM.NE.0)GO TO 400
      G(I)=(RHO*(2.*PI*L(I))**2)*(FSYS(I)/F)**2/10.**6
      DR(I)=D
      SS(I)=(RCFA/(FSYS(I)**2))*TORMS(I)*SF*(DIA(I)/(3.*L(I)))/10.
  400 CONTINUE
C
C   WRITE CALCULATED DATA
C
      DO 500 I=ISTART,ISTOP
      LCT=I
      WRITE(OD,140)LCT,TIME(I),AS(I),VR(I),SO(I),MODE(I),CYC(I),SS(I),G
     1(I),DR(I)
  500 CONTINUE
      LCT=ISTOP
      IF(ISTOP.EQ.NDP) GO TO 600
      NP=NP+1
      GO TO 45
  600 GO TO 1
  999 STOP
      END
```

```
C*****************************************
      SUBROUTINE RCSUB
C*****************************************
C
C.  COMPUTER SUBROUTINE FOR RESONANT COLUMN DATA REDUCTION
C
C  SUBROUTINE IS BASED ON PROGRAM WRITTEN BY V. P. DRNEVICH AND
C  D. J. SHIPPY, MARCH, 1977.  SUBROUTINE DATE MAY, 1978.
C
C
C-------------DEFINITIONS OF INPUT-OUTPUT VARIABLES-------------------
C
C  ADF        APPARATUS DAMPING FACTOR (ADF > 0.)
C  D          SPECIMEN DAMPING RATIO (0.01% < D < 35%)
C  EPSD       ERROR CRITERION FOR D (DEFAULT VALUE:  0.0001)
C  EPSF       ERROR CRITERION FOR F (DEFAULT VALUE:  0.01)
C  F          FREQUENCY FACTOR
C  ITERD      MAXIMUM NUMBER OF ITERATIONS ALLOWED FOR D (DEFAULT
C               VALUE:  40)
C  ITERF      MAXIMUM NUMBER OF ITERATIONS ALLOWED FOR F (DEFAULT
C               VALUE:  40)
C  JPA        INDICATOR OF END WHERE MEASUREMENTS WERE TAKEN:
C                JPA = 0 FOR MEASUREMENTS AT THE ACTIVE END;
C                JPA = 1 FOR MEASUREMENTS AT THE PASSIVE END.
C  MMF        MODIFIED MAGNIFICATION FACTOR (MMF > 0.)
C  P          PASSIVE-END INERTIA RATIO (P > 0.;  IF JPA = 0, THEN
C             P > 100. AND P > T)
C  SF         STRAIN FACTOR
C  T          ACTIVE-END INERTIA FACTOR (T > -10.)
C
C---------------------------------------------------------------------
C
C        GIVEN VALUES OF T, P, ADF, MMF, AND JPA, THIS PROGRAM CALCU-
C  LATES VALUES OF F, D, AND SF AND WILL PRINT VALUES OF ALL THESE
C  PARAMETERS.
C
C
C
      DIMENSION C(4),UP(11)
      REAL MMF,MMFCAL
      INTEGER OD
      COMMON /VALS/P,T,ADF,MMF,JPA,AMP,D,F,SF /DLIM/DL,DR
      COMMON /ALARM/KALARM /EPSIT/EPSF,ITERF,EPSD,ITERD
      COMMON /PAR/PL,QL,C/MAP/MAL
      COMMON /CRIT/MMFCAL,PHASE
      EXTERNAL DELAMP
 1110 FORMAT(49H * * * * *   W A R N I N G   * * * * *   POSSIBLY,
     1    23H NOT ENOUGH ITERATIONS )
 1115 FORMAT(50H TO OBTAIN SPECIFIED ACCURACY FOR D WITH THE ABOVE,
     1    18H PARAMETER VALUES.)
 1117 FORMAT(30H  TRY A LARGER VALUE OF ITERD.)
 1120 FORMAT(46H * * * * *   E R R O R   * * * * *   THE VALUE,
     1    19H OF D FOR THE ABOVE)
 1125 FORMAT(46H PARAMETERS LIES OUTSIDE THE ALLOWABLE RANGE, ,
```

```
     1    14H0.001 TO 0.35.)
 1220 FORMAT(3(1X,F9.4),1X,F9.5,1X,I1,2(1X,F9.6),1X,1PE9.3,
     1    2(1X,0PF9.5))
 1225 FORMAT(55H * * * * *   E R R O R   * * * * *   MMF MUST BE .GT.0.)
 1230 FORMAT(53H * * * * *   E R R O R   * * * * *   P MUST BE .GE.0.)
 1240 FORMAT(50H * * * * *   E R R O R   * * * * *   IF(JPA.EQ.0) ,
     1    19H P MUST BE .GE.100.)
 1250 FORMAT(50H * * * * *   E R R O R   * * * * *   IF(JPA.EQ.0) ,
     1    17H P MUST BE .GE. T)
 1260 FORMAT(55H * * * * *   E R R O R   * * * * *   T MUST BE .GE.-10.)
 1270 FORMAT(55H * * * * *   E R R O R   * * * * *   ADF MUST BE .GE.0.)
 1280 FORMAT(54H * * * * *   E R R O R   * * * * *   MF MUST BE .GT.0.)
 1310 FORMAT(49H * * * * *   W A R N I N G   * * * * *   POSSIBLY,
     1    23H NOT ENOUGH ITERATIONS )
 1315 FORMAT(50H TO OBTAIN SPECIFIED ACCURACY FOR F WITH THE ABOVE,
     1    12H PARAMETERS.)
 1317 FORMAT(30H  TRY A LARGER VALUE OF ITERF.)
 1320 FORMAT(48H * * * * *   E R R O R   * * * * *   THERE IS NO,
     1    10H RESONANCE)
 1330 FORMAT(51H  (DISPLACEMENT ONE-QUARTER CYCLE OUT OF PHASE WITH,
     1    19H FORCING FUNCTION) )
 1340 FORMAT(25H FOR THE ABOVE PARAMETERS)
 1350 FORMAT(51H * * * * *   W A R N I N G   * * * * *   BECAUSE OF,
     1    16H LARGE APPARATUS)
 1360 FORMAT(49H  DAMPING, THE CALCULATED AMPLITUDE IS RELATIVELY,
     1    15H INSENSITIVE TO)
 1365 FORMAT(49H  SPECIMEN DAMPING.  CONSEQUENTLY, THE CALCULATED,
     1 17H SPECIMEN DAMPING)
 1367 FORMAT(37H  RATIO ABOVE MAY BE VERY INACCURATE.)
C  SET INPUT AND OUTPUT DEVICE CODES
      ID = 5
      OD = 6
      EPSD = 1.E-4
      ITERD = 40
      EPSF = 1.E-2
      ITERF = 40
   10 CONTINUE
      MAL = 0
      IF(MMF.GT.0.) GO TO 15
      MAL = MAL + 1
      IF(MAL.EQ.1) WRITE(OD,1220) P,T,ADF,MMF,JPA
      WRITE(OD,1225)
   15 IF(P.GE.0.)  GO TO 20
      MAL = MAL + 1
      IF(MAL.EQ.1)  WRITE(OD,1220) P,T,ADF,MMF,JPA
      WRITE(OD,1230)
   20 IF(JPA.EQ.1.OR.P.GE.100.)  GO TO 30
      MAL = MAL + 1
      IF(MAL.EQ.1)  WRITE(OD,1220) P,T,ADF,MMF,JPA
      WRITE(OD,1240)
   30 IF(JPA.EQ.1.OR.T.LE.P)  GO TO 40
      MAL = MAL + 1
      IF(MAL.EQ.1)  WRITE(OD,1220) P,T,ADF,MMF,JPA
      WRITE(OD,1250)
```

```
 40 IF(T.GE.-10.)  GO TO 50
    MAL = MAL + 1
    IF(MAL.EQ.1)  WRITE(OD,1220) P,T,ADF,MMF,JPA
    WRITE(OD,1260)
 50 IF(ADF.GE.0.)  GO TO 60
    MAL = MAL + 1
    IF(MAL.EQ.1)  WRITE(OD,1220) P,T,ADF,MMF,JPA
    WRITE(OD,1270)
 60 IF(MMF.GT.0.)  GO TO 70
    MAL = MAL + 1
    IF(MAL.EQ.1)  WRITE(OD,1220) P,T,ADF,MMF,JPA
    WRITE(OD,1280)
 70 IF(MAL.NE.0)  GO TO 190
    KALARM = 0
    DL = 0.0001
    DR = .35
    CALL RTMI2(D,AMPDEL,DELAMP,DL,DR,EPSD,ITERD,IER)
    IF(KALARM.NE.1)  GO TO 80
    MAL = MAL + 1
    IF(MAL.EQ.1)  WRITE(OD,1220) P,T,ADF,MMF,JPA
    WRITE(OD,1320)
    WRITE(OD,1330)
    WRITE(OD,1340)
    GO TO 190
 80 IF(IER.NE.2)  GO TO 90
    MAL = MAL + 1
    IF(MAL.EQ.1)  WRITE(OD,1220) P,T,ADF,MMF,JPA
    WRITE(OD,1120)
    WRITE(OD,1125)
    GO TO 190
 90 CONTINUE
    DO 180 I=1,11
    XR = (I-1)/10.
    QLX = QL*XR
    PLX = PL*XR
    CC = COSH(QLX)*COS(PLX)
    SC = SINH(QLX)*COS(PLX)
    SS = SINH(QLX)*SIN(PLX)
    CS = COSH(QLX)*SIN(PLX)
    UP(I) = C(1)*(-PL*CS+QL*SC) + C(2)*(-PL*SS+QL*CC) +
   1   C(3)*(PL*SC+QL*CS) + C(4)*(PL*CC+QL*SS)
180 CONTINUE
    GAM = (UP(1)+UP(11)+4.*(UP(2)+UP(4)+UP(6)+UP(8)+UP(10))
   1   +2.*(UP(3)+UP(5)+UP(7)+UP(9)))/30.
    SF = ABS(GAM*F**2/MMF)
     D = D*100.
    IF(IER.NE.1)  GO TO 110
    WRITE(OD,1110)
    WRITE(OD,1115)
    WRITE(OD,1117)
110 IF(KALARM.NE.2)  GO TO 120
    WRITE(OD,1350)
    WRITE(OD,1360)
    WRITE(OD,1365)
```

```
      WRITE(OD,1367)
  120 IF(KALARM.NE.4)  GO TO 140
      WRITE(OD,1310)
      WRITE(OD,1315)
      WRITE(OD,1317)
  140 CONTINUE
  190 RETURN
      END
C***********************
      FUNCTION DELAMP(D)
C***********************
      COMMON /VALS/P,T,ADF,MMF,JPA,AMP,DD,F,SF /DLIM/DL,DR
      COMMON /ALARM/KALARM /EPSIT/EPSF,ITERF,EPSD,ITERD
      EXTERNAL VFCN
      INTEGER OD
      REAL MMF
      OD = 6
      DD = D
      IF(T.LT.0.)  GO TO 30
      AA = -48*T*P - 7*(T+P) - 1
      BB = 48*T*P + 20*(T+P) + 5
      CC = -4*(T+P) - 4
      BD2A = BB/(2*AA)
      F = SQRT(12*(-BD2A-SQRT(BD2A**2-CC/AA)))
      FL = .8*F
      FR = 1.2*F
      GO TO 60
   30 IF(T.LT.-.1)  GO TO 40
      FL = 1.4
      FR = 1.5*FL
      GO TO 60
   40 FL = 1.75
      FR = 1.5*FL
   60 CONTINUE
      CALL RTMI(F,V,VFCN,FL,FR,EPSF,ITERF,IER)
      IF(IER.NE.2)  GO TO 70
      FL = .99*FR
      FR = 1.5*FR
      IF(FL.LE.8.)  GO TO 60
      KALARM = 1
      GO TO 120
   70 IF(IER.EQ.1)  KALARM = 4
   90 CONTINUE
      V = VFCN(F)
      A   = AMP
      AM   = MMF/F**2
      DELAMP = A - AM
      IF(D.EQ.DL)  DELL = DELAMP
      IF(D.EQ.DL)  AML = A
      IF(D.NE.DR)  GO TO 120
      DELR = DELAMP
      AMR = A
      DIF = AML - AMR
      RELDIF = DIF/AML
```

```
      IF(RELDIF.LE.0.20)  KALARM = 2
  120 CONTINUE
      RETURN
      END
C************************
      FUNCTION VFCN(F)
C***********************
      DIMENSION A(4,4),C(4)
      INTEGER OD
      REAL MMFCAL
      COMMON /VALS/P,T,ADF,MMF,JPA,AMP,D,FF,SF
      COMMON /PAR/PL,QL,C
      COMMON /CRIT/MMFCAL,PHASE
      OD = 6
      BETA = SQRT(1.+(2.*D)**2)
      PL = F*SQRT((BETA+1.)/2.)/BETA
      QL = F*SQRT((BETA-1.)/2.)/BETA
      SNHQ = SINH(QL)
      CSHQ = COSH(QL)
      SNP = SIN(PL)
      CSP = COS(PL)
      CS = CSHQ*SNP
      SC = SNHQ*CSP
      SS = SNHQ*SNP
      CC = CSHQ*CSP
      CSSC = -PL*CS + QL*SC
      SSCC = -PL*SS + QL*CC
      SCCS = PL*SC + QL*CS
      CCSS = PL*CC + QL*SS
      PF2 = P*F**2
      A(1,1) = T*F**2
      A(1,2) = QL - 2*D*PL
      A(1,3) = - ADF*F**2
      A(1,4) = PL + 2*D*QL
      A(2,1) = -A(1,3)
      A(2,2) = -A(1,4)
      A(2,3) = A(1,1)
      A(2,4) = A(1,2)
      A(3,1) = CSSC - 2.*D*SCCS - PF2*CC
      A(3,2) = SSCC - 2.*D*CCSS - PF2*SC
      A(3,3) = SCCS + 2.*D*CSSC - PF2*SS
      A(3,4) = CCSS + 2.*D*SSCC - PF2*CS
      A(4,1) = -A(3,3)
      A(4,2) = -A(3,4)
      A(4,3) = A(3,1)
      A(4,4) = A(3,2)
      C(1) = 0
      C(2) = -1.
      C(3) = 0
      C(4) = 0
      EPS = 1.E-5
      NN = 4
      CALL  GELG(C,A,NN,1,EPS,IER,NN*NN,NN)
      U0 = C(1)
```

```
      V0 = C(3)
      AMPL0 = SQRT(U0**2 + V0**2)
      PHASE0 = ATAN2(V0,U0)
      IF(PHASE0.LT.0.)  PHASE0 = PHASE0 + 6.283185
      UL = C(1)*CC + C(2)*SC + C(3)*SS + C(4)*CS
      VL = C(3)*CC + C(4)*SC - C(1)*SS - C(2)*CS
      AMPLL = SQRT(UL**2 + VL**2)
      PHASEL = ATAN2(VL,UL)
      IF(JPA.EQ.0)  VFCN = PHASE0 - 3.141593
      IF(JPA.NE.0)  VFCN = PHASEL
      IF(JPA.EQ.0)  AMP = AMPL0
      IF(JPA.NE.0)  AMP = AMPLL
      MMFCAL = AMP*F**2
      PHASE = VFCN
      RETURN
      END
C*****************************************************************
      SUBROUTINE RTMI2(X,F,FCT,XLI,XRI,EPS,IEND,IER)
C*****************************************************************
      COMMON /ALARM/KALARM
      IER=0
      XL=XLI
      XR=XRI
      X=XL
      TOL=X
      F=FCT(TOL)
      IF(KALARM.EQ.1)  RETURN
      IF(F)1,16,1
    1 FL=F
      X=XR
      TOL=X
      F=FCT(TOL)
      IF(KALARM.EQ.1)  RETURN
      IF(F)2,16,2
    2 FR=F
      IF(SIGN(1.,FL)+SIGN(1.,FR))25,3,25
    3 I=0
      TOLF=100.*EPS
    4 I=I+1
      DO 13 K=1,IEND
      X=.5*(XL+XR)
      TOL=X
      F=FCT(TOL)
      IF(KALARM.EQ.1)  RETURN
      IF(F)5,16,5
    5 IF(SIGN(1.,F)+SIGN(1.,FR))7,6,7
    6 TOL=XL
      XL=XR
      XR=TOL
      TOL=FL
      FL=FR
      FR=TOL
    7 TOL=F-FL
      A=F*TOL
```

```
      A=A+A                                                  RCS03250
      IF(A-FR*(FR-FL))8,9,9                                  RCS03260
    8 IF(I-IEND)17,17,9                                      RCS03270
    9 XR=X                                                   RCS03280
      FR=F                                                   RCS03290
      TOL=EPS                                                RCS03300
      A=ABS(XR)                                              RCS03310
      IF(A-1.)11,11,10                                       RCS03320
   10 TOL=TOL*A                                              RCS03330
   11 IF(ABS(XR-XL)-TOL)12,12,13                             RCS03340
   12 IF(ABS(FR-FL)-TOLF)14,14,13                            RCS03350
   13 CONTINUE                                               RCS03360
      IER=1                                                  RCS03370
   14 IF(ABS(FR)-ABS(FL))16,16,15                            RCS03380
   15 X=XL                                                   RCS03390
      F=FL                                                   RCS03400
   16 RETURN                                                 RCS03410
   17 A=FR-F                                                 RCS03420
      DX=(X-XL)*FL*(1.+F*(A-TOL)/(A*(FR-FL)))/TOL            RCS03430
      XM=X                                                   RCS03440
      FM=F                                                   RCS03450
      X=XL-DX                                                RCS03460
      TOL=X                                                  RCS03470
      F=FCT(TOL)                                             RCS03480
      IF(KALARM.EQ.1)  RETURN                                RCS03490
      IF(F)18,16,18                                          RCS03500
   18 TOL=EPS                                                RCS03510
      A=ABS(X)                                               RCS03520
      IF(A-1.)20,20,19                                       RCS03530
   19 TOL=TOL*A                                              RCS03540
   20 IF(ABS(DX)-TOL)21,21,22                                RCS03550
   21 IF(ABS(F)-TOLF)16,16,22                                RCS03560
   22 IF(SIGN(1.,F)+SIGN(1.,FL))24,23,24                     RCS03570
   23 XR=X                                                   RCS03580
      FR=F                                                   RCS03590
      GO TO 4                                                RCS03600
   24 XL=X                                                   RCS03610
      FL=F                                                   RCS03620
      XR=XM                                                  RCS03630
      FR=FM                                                  RCS03640
      GO TO 4                                                RCS03650
   25 IER=2                                                  RCS03660
      RETURN                                                 RCS03670
      END                                                    RCS03680
```

APPENDIX B: COMPUTER PROGRAMS ASSOCIATED WITH TORSIONAL SIMPLE SHEAR TESTS

```
100 REM  SADCYC.BB DATA ACQUISITION FOR QUASISTATIC CYCLIC STRAIN CONTROL
110 REM    SHEAR TESTS WHERE BOTH CELL PRESSURE AND CELL PRESSURE
115 REM    MINUS PORE PRESSURE ARE MEASURED.
120 REM  ORIG. PROGRAM QSCSHA.BA WRITTEN BY R.J.EBELHAR, 1/31/77
125 REM  REVISED BY J.D.OSTROW, 1/4/78
130 REM  REVISED AND RENAMED BY V.P.DRNEVICH, 2/23/78.
135 REM  MODIFIED BY V.P.D., 7/14/78 FOR STRAIN CONTROL
140 REM  CHARACTERISTICS OF THE PROGRAM:
145 REM    VARIABLE FREQUENCY (MAXIMUM FREQUENCY = 0.25 HZ)
150 REM    ROTATION TRANSDUCERS CONNECTED TO CHANNEL NO. 1
160 REM    LOAD (TORQUE) TRANSDUCER CONNECTED TO CHANNEL NO. 2
170 REM    DIFFERENTIAL PRESSURE TRANSDUCER CONNECTED TO CHANNEL NO. 3
180 REM    AXIAL DEFORMATION TRANSDUCER CONNECTED TO CHANNEL 4
185 REM    CELL PRESSURE TRANSDUCER CONNECTED TO CHANNEL NO. 5
190 REM    START-STOP SWITCH W/ OUTPUT > 0.8 VOLT CONNECTED TO CHAN.NO.0
240 DIM A(110),B(110),G(110),S1(110),P1(110),L1(110),P(110),R(110)
250 DIM H7(110),V9(110),E$(72)
260 DIM A$(15),C$(20),F$(15),F1$(15),F2$(15),C9$(10),G$(72),H$(72)
270 UDEF INI(N),PLY(Y),DLY(N),DIS(S,E,N,X)
280 UDEF SAM(C,N,P,T),CLK(R,O,S),CLW(N),ADC(N)
290 PRINT\PRINT"SADCYC.BB - CYCLIC SHEAR TEST DATA ACQUISITION PROGRAM"
300 PRINT"TEST NUMBER (6 SYMB. MAX.)";\INPUT A$\PRINT"DATE";\INPUT C$
310 PRINT"SPECIMEN INFORMATION"\PRINT"DIAMETER IN MM.";\INPUT D2
330 PRINT"LENGTH IN MM.";\INPUT D3\PRINT"CALIBRATION DATA"
335 PRINT"INPUT INITIAL LENGTH LVDT RDG. (VOLTS)";\INPUT A9
340 PRINT"ROTATION C.F. (RAD/VOLT)";\INPUT R6
350 PRINT"TORQUE C.F. (N-M/VOLT)";\INPUT B6
355 PRINT"DIFFERENTIAL PRESSURE TRANS. C.F. (KPA/VOLT)";\INPUT C6
360 PRINT"CELL PRESSURE TRANS. C.F. (KPA/VOLT)";\INPUT C8
365 PRINT"AXIAL DEFORM. C.F. (MM/VOLT)";\INPUT A6
367 PRINT"PERIOD IN SECONDS";\INPUT S5\S7=S5/50.
370 PRINT"ELAPSED TIME IN MINUTES ";\INPUT S0\D4=D2*D2*D2*D2
371 PRINT"REMARKS (72 CHAR. MAX.)"\INPUT E$
372 PRINT"USE START SWITCH TO INITIALIZE READINGS, THEN SWITCH OFF"
375 T9=ADC(0)\IF ABS(T9)>400 THEN 376\GO TO 375
376 R9=ADC(1)\T9=ADC(0)\Z5=ADC(5)\IF ABS(T9)>400 THEN 376
377 Z5=Z5*C8/511\Z5=INT(Z5*10+0.5)/10
378 PRINT"CELL PRESSURE = ";Z5;" KPA"
379 PRINT\PRINT"READINGS INITIALIZED, USE START SWITCH TO BEGIN"
380 G$="CYCLE   SH.STRAIN   SH.MOD.   EFF.STRESS    DEFORM.     DAMP.RATIO"
390 H$=" NO.        (%)        (MPA)        (KPA)          (MM)        (%)"
400 PRINT\PRINT G$;H$\PRINT\J9=0\T0=0\Y=CLK(5,1000,0)
410 T9=ADC(0)\IF ABS(T9)<400 THEN 410
420 R0=ADC(1)\R0=R0-R9\IF R0<0 THEN 420
425 B(0)=ADC(2)\T0=0
426 IF B(0)<0. THEN 427\B(0)=B(0)*B6/511\GO TO 430
427 B(0)=B(0)*B6/512
430 T1=0.\A8=0.\P8=0.\M1=0.\V2=0.\R(0)=0.
435 T1=0.
440 Y=CLW(0)\T1=T1+1\T7=T1/100.\IF T7<S7 THEN 440\T0=T0+1
450 T9=ADC(0)\R(T0)=ADC(1)\B(T0)=ADC(2)\P(T0)=ADC(3)\A(T0)=ADC(4)
460 R(T0)=R(T0)-R9
470 IF T9>400 GO TO 480\IF T9<-400 GO TO 480\GO TO 660
```

```
480 IF A(T0)<0 GO TO 490\A(T0)=(A(T0)/511-A9)*A6\GO TO 500
490 A(T0)=(A(T0)/512-A9)*A6
500 IF B(T0)<0 GO TO 510\B(T0)=B(T0)*B6/511\GO TO 520
510 B(T0)=B(T0)*B6/512
520 IF P(T0)<0 GO TO 530\P(T0)=P(T0)*C6/511\GO TO 540
530 P(T0)=P(T0)*C6/512
540 IF R(T0)<0 THEN 550\R(T0)=R(T0)*R6/511\GO TO 555
550 R(T0)=R(T0)*R6/512
555 B3=R(T0)*R(T0)\B4=R(T0)-R(T0-1)
557 IF B4<0. THEN 558\B(T0)=B(T0)-0.00155\GO TO 560
558 B(T0)=B(T0)+0.00155
560 A8=A8+A(T0)\P8=P8+P(T0)\IF M1>B3 THEN 570\M1=B3\J7=T0
570 IF R(T0)<0. THEN 580\IF R(T0-1)<0. THEN 590\GO TO 435
580 IF R(T0-1)>0. THEN 590\GO TO 435
590 J9=J9+1\L1(J9)=A8/T0\P1(J9)=P8/T0\M4=(B(T0)-B(T0-1))/(R(T0)-R(T0-1))
600 B2=B(T0)-M4*R(T0)\C7=B(J7)-(B2+B(0))/2.\K0=C7/R(J7)
610 V3=0.5*R(T0-1)*(B2+B(T0-1))\L4=D3-L1(J9)\G(J9)=10.18592*K0*L4/D4
640 H4=0.5*R(J7)*C7\S1(J9)=R(J7)*D2/(3.*L4)\R(0)=0.\B(0)=B2\V2=V2-V1+V3
650 H7(J9)=15.915*V2/H4\IF J9=101 THEN 660\T0=0\GO TO 430
660 J=J9/2\J=INT(J)
670 FOR I=1 TO J\J8=2*I\A(I)=(ABS(S1(J8))+ABS(S1(J8-1)))/2
672 B(I)=(G(J8)+G(J8-1))/2.\P(I)=(P1(J8)+P1(J8-1))/2.
673 A(I)=A(I)*100.\B(I)=B(I)*1000.
674 R(I)=(L1(J8)+L1(J8-1))/2.\V9(I)=(H7(J8)+H7(J8-1))/2.\NEXT I
676 FOR I=1 TO J\PRINT TAB(2);I;TAB(8);A(I);TAB(20);B(I);
680 PRINT TAB(30);P(I);TAB(43);R(I);TAB(57);V9(I)\NEXT I
681 X0=0\X1=0\X2=0\X3=0\X4=0
682 FOR I=1 TO J\X0=X0+A(I)\X1=X1+B(I)
683 X2=X2+P(I)\X3=X3+R(I)\X4=X4+V9(I)\NEXT I
684 X0=X0/J\X1=X1/J\X2=X2/J\X3=X3/J\X4=X4/J
685 PRINT\PRINT"AVERAGE VALUES"
686 PRINT TAB(8);X0;TAB(20);X1;TAB(30);X2;TAB(43);X3;TAB(57);X4
690 PRINT\PRINT"DO YOU WISH TO WRITE THIS TEST ON TAPE? Y=YES, N=NO";
700 INPUT Q$\IF Q$="N" THEN 750\F1$="DTA1:"\F2$=".QS"\F$=F1$&A$&F2$
710 FILEV#1:F$\PRINT#1:A$\PRINT#1:C$\PRINT#1:(J+1)
720 PRINT#1:D2,D3,S5\PRINT#1:A6,B6,C6,R6,C8
730 FOR K=1 TO J\PRINT#1:K,A(K),B(K),P(K),R(K),V9(K)\NEXT K
735 PRINT#1:K,X0,X1,X2,X3,X4\CLOSE#1
740 PRINT"FILE ";F$;" HAS BEEN CREATED.";
750 PRINT"DO YOU WISH TO RUN ANOTHER TEST? Y=YES, N=NO";\INPUT Q$
760 IF Q$="N" THEN 890
770 PRINT"LINE FEED PAPER TO TOP OF NEXT SHEET, PUSH (CR) TO CONTINUE"
780 INPUT Q9
785 PRINT"SADCYC.BA - CYCLIC SHEAR TEST DATA ACQUISITION PROGRAM"
790 PRINT"TEST NUMBER (6 SYMB. MAX.)";\INPUT A$
795 PRINT"DATE ";C$
800 PRINT"SPECIMEN INFORMATION:"\PRINT"DIAMETER IN MM = ";D2
805 PRINT"LENGTH IN MM = ";D3
810 PRINT"CALIBRATION DATA:"\PRINT"INIT. LENGTH LVDT RDG.(VOLTS) = ";A9
815 PRINT"ROTATION C.F.(RAD/VOLT) = ";R6
825 PRINT"TORQUE C.F. (N-M/VOLT) = ";B6
830 PRINT"DIFFERENTIAL PRESSURE TRANS. C.F. (KPA/VOLT) = ";C6
835 PRINT"CELL PRESSURE TRANSDUCER C.F. (KPA/VOLT) = ";C8
837 PRINT"AXIAL DEFORM. C.F. (MM/VOLT) = ";A6
```

```
840 PRINT"PERIOD IN SECONDS = "; S5
842 FOR I=1 TO 109\R(I)=0.\B(I)=0.\A(I)=0.\P(I)=0.\V9(I)=0.\NEXT I
845 GO TO 370
890 END

READY
```

```
1 PRINT\PRINT"SADLT.BA, DATA ACQUI FOR LARGE SHEAR TEST & USES DIFF. TRANS"
5 PRINT"INITIAL POSITION OF ROTATION DEC. SWITCH SHOULD BE AT 1."
8 REM  PROG. FORMERLY CALLED QSCHLD.BA. MOD. 7/14/78 BY V.P.D.
10 DIM M(200),T(200),D(200),L(200),C(200),P(200),E(200),S(200)
15 DIM R(200),Z(200),R1(200)
20 DIM B$(20),C$(50),E$(72),G$(72),F$(72),H$(72),I$(15)
23 UDEF INI(N),PLY(Y),DLY(N),DIS(S,E,N,X)
26 UDEF SAM(C,N,P,T),CLK(R,O,S),CLW(N),ADC(N)
30 PRINT"QUASISTATIC CYCLIC SHEAR LONG TERM TEST DATA ACQUISITION PROGRAM"
40 PRINT\PRINT"TEST NUMBER (6 SYMBOLS MAX.)";\INPUT A$\PRINT"DATE";\INPUT B$
75 PRINT"SPECIMEN INFORMATION"
80 PRINT"SPECIMEN DIAMETER (MM)";\INPUT D1\PRINT"SPECIMEN LENGTH (MM)";
85 INPUT L1\PRINT"CALIBRATION DATA"
95 PRINT"INITIAL LENGTH LVDT READING";\INPUT L9
100 PRINT"ROTATION C.F.(RAD/VOLT)";\INPUT R6\PRINT"TORQUE C.F.(N-M/VOLT)";
110 INPUT T6\PRINT"DIFFER. PRESSURE C.F.(KPA/VOLT)";\INPUT P6
120 PRINT"CELL PRESSURE C.F.(KPA/VOLT)";\INPUT C6\PRINT"DEF. C.F.(MM/VOLT)";
130 INPUT D6\PRINT"INITIAL CELL PRESSURE (KPA)";\INPUT C7
132 PRINT"GMAX (MPA)";\INPUT G1\PRINT"ESTIMATED TMAX (KPA)";\INPUT T1
134 PRINT"SPEC. WEIGHT (GRAMS)";\INPUT W1\A1=32/(3*3.14159*(D1/1000)^3)
140 PRINT"READING INTERVAL (MIN)";\INPUT M1\PRINT"APPROX.PERIOD (MIN)";
142 INPUT S8\PRINT"SOIL TYPE";\INPUT C$\PRINT"ELAPSED TIME (MIN)";
144 INPUT D$\PRINT"REMARKS (72 CHAR. MAX.)"\INPUT E$
150 M2=M1-0.03\PRINT
160 F$="TIME    EFF.      SHEAR     SHEAR     AXIAL      P.P.        T/TMAX"
170 G$="(MIN)   STRESS    STRESS    STRAIN    STRAIN     CHANGE"
180 H$="        (KPA)     (KPA)      (%)       (%)       (KPA)"
190 PRINT"USE START SWITCH TO INITIALIZE READINGS, THEN SWITCH OFF."
200 M9=ADC(0)\IF ABS(M9)>400 THEN 210\GO TO 200
210 R9=ADC(1)\T9=ADC(6)\C9=ADC(5)\P9=ADC(3)\M9=ADC(0)\IF ABS(M9)>400 THEN 210
211 IF C9<0 THEN 212\C9=C9*C6/511\GO TO 213
212 C9=C9*C6/512
213 IF P9<0 THEN 214\P9=P9*P6/511\GO TO 215
214 P9=P9*P6/512
215 E8=P9
220 PRINT"READINGS INITIALIZED. USE START SWITCH TO BEGIN."
230 PRINT\PRINT\PRINT F$\PRINT G$\PRINT H$
240 M9=ADC(0)\IF M9>400 THEN 250\IF M9<-400 THEN 250\GO TO 240
250 N0=0\M3=0\M4=0\M5=0\S1=1.0\I=0\Y=CLK(3,600,0)
255 GO TO 280
260 Y=CLW(0)\M9=ADC(0)\IF M9>400 THEN 270\IF M9<-400 THEN 270\GO TO 900
270 M4=M4+1.\M5=M4/100.\IF M5<M2 THEN 260
280 M9=ADC(0)\R=ADC(1)\T=ADC(6)\P=ADC(3)\D=ADC(4)\C=ADC(5)
290 I=I+1\R1(I)=ABS(R)\IF S1<.2 THEN 400\X0=.2*R1(I-1)
295 IF R1(I)<X0 THEN 300\GO TO 400
300 PRINT"SWITCH ON ROTATION OUTPUT HAS BEEN SET TO 0.1X POSITION"
315 R6=R6*10.\S1=0.1\R9=R9*.1\GO TO 400
400 R=R-R9\T=T-T9
500 IF R<0 THEN 502\R(I)=R/511\GO TO 520
502 R(I)=R/512
520 R=R(I)*R6
525 IF T<0 THEN 530\T=T*T6/511\GO TO 540
530 T=T*T6/512
```

```
540 IF P<0 THEN 550\P=P*P6/511\GO TO 560
550 P=P*P6/512
560 IF C<0 THEN 570\C=C*C6/511\GO TO 580
570 C=C*C6/512
580 IF D<0 THEN 590\D=(D/511-L9)*D6\GO TO 600
590 D=(D/512-L9)*D6
600 NO=NO+1
700 M(NO)=M3\T(NO)=T*A1/1000\L2=L1-D\D(NO)=R*D1*100/3/L2\L(NO)=(D/L1)*100
750 C(NO)=C\P(NO)=P\E=P\E(NO)=E8-E\S(NO)=T(NO)/T1
755 Z(NO)=E\Z(NO)=INT(Z(NO)*10^1+0.5)/10^1
760 M(NO)=INT(M(NO)*10^3+0.5)/10^3\T(NO)=INT(T(NO)*10^3+0.5)/10^3
770 D(NO)=INT(D(NO)*10^5+0.5)/10^5\L(NO)=INT(L(NO)*10^3+0.5)/10^3
780 E(NO)=INT(E(NO)*10^3+0.5)/10^3\S(NO)=INT(S(NO)*10^4+0.5)/10^4
800 PRINT M(NO);TAB(10);Z(NO);TAB(17);T(NO);TAB(27);D(NO);TAB(37);L(NO);
810 PRINT TAB(47);E(NO);TAB(60);S(NO)
820 M4=0\M5=0\M3=M3+M1\GO TO 260
900 PRINT\PRINT"DO YOU WISH TO WRITE RESULTS ON TAPE (Y=YES,N=NO)";
910 INPUT Q$\IF Q$="N" THEN 970\F1$="DTA1:"\F2$=".BB"\I$=F1$&A$&F2$
920FILEV#1:I$\PRINT#1:A$\PRINT#1:B$\PRINT#1:C$\PRINT#1:D$\PRINT#1:E$
930 PRINT#1:G1,T1,D1,L1,W1\PRINT#1:R6,T6,P6,D6,C6\PRINT#1:NO,C7,S8,L9
940 FOR K=1 TO NO\PRINT#1:M(K),T(K),D(K),L(K),Z(K)
950 PRINT#1:E(K),S(K),C(K),P(K)\NEXT K\CLOSE#1
960 PRINT"FILE ";I$;" HAS BEEN CREATED."
970 PRINT"DO YOU WISH TO RUN ANOTHER TEST (Y=YES,N=NO)";\INPUT Q$
980 IF Q$="N" THEN 1000\PRINT"ADVANCE TO NEXT PAGE, HIT RETURN TO BEGIN."
990 INPUT Q9\GO TO 10
1000 END

READY
```

```
100 REM NORMAL.DA IS A PROGRAM TO CALCULATE NORMALIZED VALUES
105 REM  OF SHEAR STRESS, STRAIN, SHEAR MODULUS FROM QUASISTATIC
110 REM  SIMPLE SHEAR TESTS DURING FIRST ONE-QUARTER OF LOADING CYCLE.
115 REM  DATA IS WRITTEN INTO FILES WITH SADLT.BA PROGRAM.
120 REM  WRITTEN BY V.P.D. AND J.D.O., FEB.16, 1978.
130 REM  MODIFIED AND UP DATED BY V.P.D. AND J.P.K., AUG.15, 1978.
135 REM  FURTHER MOD. 8/22/78 TO ACCOUNT FOR SLIGHTLY POS. STRAIN
136 REM  FOR FIRST DATA SET.  INPUT FROM FILE ALSO CLEANED UP.
200 DIM E$(72),I$(15),T(200),D(200),E(200),Z(200),Q(200)
220 DIM D7(200),T7(200),G6(200),G7(200),H$(72),L$(72),M$(72)
250 PRINT"NORMALIZED STRESS-STRAIN DATA"\PRINT
300 PRINT"INPUT TEST DESIGNATION-";\INPUT A$
305 PRINT"INPUT NUMBER OF DATA POINTS-";\INPUT I
310 F1$="DTA1:"\F2$=".BB"\I$=F1$&A$&F2$
320 FILE#1:I$\INPUT#1:E$\INPUT#1:E$\INPUT#1:E$\INPUT#1:E$\INPUT#1:E$,C
330 INPUT#1:C4,C4,C4,C4,C4,C,L\INPUT#1:C4,C4,C4,C4,C4,C,L
340 INPUT#1:C4,C4,C4,C4,C,L
350 FOR K=1 TO I\INPUT#1:C2,T(K),D(K),C2,C2,C,L
360 INPUT#1:E(K),C2,C2,Z(K),C,L\NEXT K
370 CLOSE#1
400 PRINT"ANGLE OF SHEARING RESISTANCE (EFF. STRESS) IN DEGREES-";
405 INPUT P1
410 PRINT"COHESION (EFF. STRESS) IN KPA-";\INPUT C1
415 REM CALC. INITIAL CONFINING STRESS
420 S0=Z(1)
425 REM CALC. REF. TMAX FROM HARDIN & DRNEVICH.
430 P2=3.14159
435 T9=S0*SIN(P1*P2/180.)+C1*COS(P1*P2/180.)
437 PRINT"INITIAL REFERENCE STRENGTH, TMAX, IN KPA = ";T9
438 PRINT"INITIAL TANGENT MODULUS, GMAX, IN MPA-";\INPUT G9
439 D9=T9/(G9*1000.)\REM INITIAL REFERENCE STRAIN.
440 PRINT"ANY CHANGES FOR SADLT.BA DATA";\INPUT Q$
441 FOR J = 1 TO I
442 IF Q$ = "N" THEN 459
443 REM DATA CORRECTIONS FOR SHEAR STRESS, SHEAR STRAIN, EFF.STRESS.
445 PRINT"EFF. CONF. STRESS = ";\PRINT Z(J)\PRINT
446 PRINT"CHANGES?(Y OR N)";\INPUT X$
448 IF X$ = "N" THEN 459
450 PRINT" ARE YOU SURE";\INPUT Y$
451 IF Y$ = "N" THEN 446
455 PRINT "INPUT SHEAR STRESS,SHEAR STRAIN,EFF. STRESS";
456 INPUT T(J),D(J),Z(J)
457 PRINT" ARE THE NUMBERS CORRECT";\INPUT Z$
458 IF Z$ = "N" THEN  455
459 D8 = D9*SQR(Z(J)/S0)\REM REF.STRAIN CORR. FOR PRESSURE.
460 T8=T9*(Z(J)/S0)\REM SHEAR STRENGTH CORR. OFR PRESSURE.
465 D7(J)=(D(J)/100.)/D8\REM  GAMMA/GAMMA REF.
470 T7(J)=T(J)/T8\REM  T/TMAX
475 G8=G9*SQR(Z(J)/S0)\REM  GMAX CORR FOR PRESSURE.
477 IF ABS(D(J)) > 0.0005 THEN 480
478 G6(J)=G9\ GO TO 482
480 G6(J)=(T(J)/D(J))/10.\ REM SECANT SHEAR MODULUS.
482 G7(J)=G6(J)/G8
```

```
483 Q(J)=Z(J)
484 Q(J)=INT(Q(J)*10+0.5)/10\T(J)=INT(T(J)*10^2+0.5)/10^2
485 D(J)=INT(D(J)*10^5+0.5)/10^5\G6(J)=INT(G6(J)*10^2+0.5)/10^2
486 T7(J)=INT(T7(J)*10^4+0.5)/10^4\D7(J)=INT(D7(J)*10^4+0.5)/10^4
487 G7(J)=INT(G7(J)*10^4+0.5)/10^4
488 NEXT J
490 PRINT\PRINT
500 H$="EFF.CONF.    SHEAR      SHEAR      SHEAR      T/TMAX     S/SMAX  G/GMAX"
505 L$=" STRESS      STRESS    STRAIN     MODULUS"
510 M$=" (KPA)       (KPA)       (%)        (MPA) "
515 PRINT H$
520 PRINT L$
525 PRINT M$
550 FOR J=1 TO I
555 PRINT Q(J);TAB(11);T(J);TAB(21);D(J);TAB(31);G6(J);
560 PRINT TAB(41);T7(J);TAB(51);D7(J);TAB(61);G7(J)
562 NEXT J
563 PRINT
564 PRINT "DO YOU WISH TO STORE THESE DATA ON TAPE?(Y=YES,N=NO)";\INPUT Q$
566 IF Q$ = "N" THEN 600
567 F2$=".NO"\I$=F1$&A$&F2$\FILEV#2:I$
568 PRINT#2:I,P1,C1,G9
569 FOR J=1 TO I
570 PRINT#2:Q(J),T(J),D(J),G6(J)
575 PRINT#2:T7(J),D7(J),G7(J)
580 NEXT J
585 CLOSE#2
590 PRINT"FILE ";I$;" HAS BEEN STORED ON TAPE."
600 PRINT"DO YOU WISH TO RUN PROGRAM AGAIN?(Y=YES,N=NO)";\INPUT Q$
605 IF Q$ = "N" THEN 999
610 PRINT "ADVANCE PAPER TO NEXT SHEET, PUSH CR.";\INPUT Q$
615 GO TO 250
999 END

READY
```

APPENDIX C: DESCRIPTION OF REMOLDED SPECIMENS

1. For the testing program to isolate the effects of stress path from those of disturbance, it was necessary to have a number of soil specimens with similar values of density, moisture content void ratio, particle size distribution, specific gravity, and isotropy. The only means to fulfill this requirement was to remold the samples from a common soil.

2. It was originally planned to use a residual clay from Fayette County, Kentucky. This clay was classified by the Unified System as a CL material with properties given in Table C1. Several specimens were formed and one was consolidated in a triaxial cell to a mean effective confining stress of 50 KPa. The time for 100% primary consolidation, obtained by plotting volume change (burette reading) against the log-of-time, was on the order of 700 minutes. It is believed that this long time for consolidation was due to the remolding process creating a dispersed clay structure with a resulting low permeability. In any event, it was decided that the soil was unsuitable to use as it was. The strain rates would have had to have been extremely low to achieve good pore pressure equalization over the sample (95% or better) at 1% strain using this clay.

3. In order to increase the permeability to an acceptable level two other constituents were added to the clay. The first component was flyash from a coal fired electric generating plant. This flyash was composed predominately of silt-size material. The second part was a monterey sand. The three elements were combined in a ratio calculated to insure that the final soil would have the highest permeability and still

be classified as cohesive. The properties for the final soil are also given in Table C1.

4. The composite soil was blended thoroughly with the amount of water necessary to bring its moisture content to about 18%. This moisture content would result in specimens with a high initial degree of saturation. It would also insure that the samples have an overconsolidation ratio near 1 (normally consolidated). After mixing, the soil was sealed in a plastic container and allowed to cure for 48 hours. This increased the probability of an even distribution of soil moisture. The soil was now ready for the compaction process.

5. The material was compacted in a length of plastic tube which was contained within a split-shell specimen mold. The inside of the tube was given a light coating of mineral oil to facilitate the extrusion of the sample.The sample mold was fixed firmly to the laboratory table top by a series of clamps.

6. Two soil compactors were used. The first had a flat head with a diameter of 318 mm (1.5 inches). This compactor was used to compress the soil into the mold. The second one had a rounded head 131 mm (0.5 inch) in diameter. It was used as a penetration device to disturb the smooth surfaces between layers that could possibly act as planes of weakness.

7. The soil was placed into the mold in four lifts. The first lift received 25 strokes with the compressing compactor. The second layer got 310 strokes, the third 315 and the fourth 40. It is believed that this increase in the amount of energy the lifts acquired would result in a more uniform density over the length of the sample. After the specimen was compacted it was carefully extruded from the mold. The rough ends were trimmed, and these trimmings were used to obtain moisture contents.

Each specimen was weighed, and measured for length and diameter. It was dipped in hot wax to prevent loss of moisture during storage. The top end of each sample was labeled so that they could be tested in the same orientation in which they were compacted.

8. Using the dimension measurements, weight and moisture content the void ratio for each specimen was calculated. The mean void ratio for all the samples was found. Only specimens that had a void ratio within two percent of the mean were used in the testing program.

9. The samples were stored for at least one week before being tested. This was to insure that any excess pore pressures formed during remolding would have time to dissipate.

TABLE C1. SUMMARY OF SOIL PROPERTIES

	SOIL FROM FAYETTE COUNTY, KENTUCKY	SOIL AFTER ADDITION OF SAND AND FLYASH
LIQUID LIMIT	42	21
PLASTIC LIMIT	24	15
SPECIFIC GRAVITY	2.76	2.68
PARTICLE SIZE ANALYSIS		
% PASSING		
NO. 10	100	100
NO. 40	83	79
NO. 200	79	57
.002 MM	36	20
CLASSIFICATION		
UNIFIED	CL	CL-ML
AASHTO	A7-6(11)	A4(5)
TEXTURAL	SILTY-CLAY	CLAY-SAND
AVERAGE COMPACTED DENSITY	2005.5 KG/M^3	2085.3 KG/M^3
MEAN VOID RATIO	.7061	.5214
MEAN WATER CONTENT	24.1%	18.4%

APPENDIX D: COMPUTER PROGRAMS FOR REDUCING TRIAXIAL/RESONANT COLUMN DATA

```
C********************       RC6B FORTRAN       ****************************
C    DATA REDUCTION PROGRAM FOR HARDIN TORSIONAL RESONANT COLUMN APP.
C
C    WRITTEN BY V.P. DRNEVICH
C
C    JULY 1978 VERSION
C
C    REVISED BY S.H. BICKEL... NOVEMBER 27, 1978
C    REVISED BY S.H. BICKEL... JANUARY 11, 1979
C
C    PARAMETER DEFINITIONS
C        APPARATUS CONSTANTS
C          MA    =TOP CAP AND OSCILLATOR(S) MASS (KG)
C          JA    =APPARATUS POLAR MASS INERTIA (KG-M**2)
C          RCFA =ROT. MOTION C.F. FOR TORS. VIB. (RAD/VRMS)*(HZ**2)
C          ADCT =APPARATUS DAMPING COEFF. FOR TORS. MOTION (KG-M**2-HZ)
C          TCF   =TORQUE-CURRENT FACTOR FOR TORSIONAL MOTION (N-M/VRMS)
C          ALCF =AXIAL LOAD CAL. FACTOR (NEWTONS/UNIT)
C          KO    =APPARTUS SPRING CONSTANT (N-M/RADIAN)
C        GENERAL CONSTANTS
C          PI    =3.14159
C          UWAT =UNIT WEIGHT OF WATER = 1000. (KG/M**3)
C        SPECIMEN VARIABLES
C          W     =SPECIMEN WEIGHT (GMS)
C          SD    =SPECIMEN DIAMETER (MM)
C          SL    =SPECIMEN LENGTH (MM)
C          SG    =SPECIFIC GRAVITY OF SPECIMEN SOLIDS
C          WC    =WATER CONTENT OF SPECIMEN (PERCENT)
C          UM    =MASS DENSITY OF SPECIMEN (KG/M**3)
C          SJ    =SPECIMEN POLAR INERTIA (M**4)
C          SINR =SPECIMEN MASS POLAR INERTIA (KG-M**2)
C          SPVR =SPECIMEN VOID RATIO
C          SAT   =DEGREE OF SATURATION (PERCENT)
C        SYSTEM VARIABLES
C          ALI   =INITIAL AXIAL LOAD RDG. (UNITS)
C          LRI   =INITIAL LENGTH DIAL READING (UNITS)
C          LCFM =LENGTH DIAL CALIBRATION FACTOR (MM/UNIT)
C          LR    =LENGTH READING (UNITS) (COMPRESSION IS POSITIVE)
C          BRI   =INITIAL BURETTE READING (UNITS)
C          BCF   =BURETTE CALIBRATION FACTOR (ML/UNIT)
C          BR    =BURETTE READING (UNITS)
C          TTOR =SYSTEM POLAR MASS INERTIA RATIO
C          TLON =SYSTEM MASS INERTIA RATIO
C          TIME =TIME OF VIBRATION (MIN)
C          CP    =CELL PRESSURE (KG/CM**2)
C          PCF   =EFFECTIVE STRESS CALIBRATION FACTOR (KPA/UNIT)
C          EFFST=EFFECTIVE STRESS (UNITS)
C          ALR   =AXIAL LOAD READING (UNITS)
C          CRRMS=TORQUE READING (VOLTS-RMS)
C          TORMS=ACCELEROMETER OUTPUT (VOLTS-RMS)
C          FSYS =SYSTEM UNDAMPED NATURAL FREQUENCY (HZ)
C        CALCULATED SOIL PARAMETERS
```

```
C         V     =VOLUME (M**3)
C         L     =LENGTH (M)
C         AS    =AXIAL STRAIN (PERCENT)
C         VR    =VOID RATIO
C         PSR   =PRINCIPAL STRESS RATIO
C         SS    =AVERAGE SHEAR OR ROD STRAIN AMPLITUDE IN SPECIMEN (%)
C         G     =ROD MODULUS OR SHEAR MODULUS (MPA)
C         DR    =DAMPING RATIO (PERCENT)
C         CYC   =CYCLES OF VIBRATION
C         SO    =MEAN EFFECTIVE PRINCIPLE STRESS (KPA)
C         E     =YOUNG'S MODULUS (MPA)
C         EMAX =INITIAL YOUNG'S MODULUS FOR AXIAL COMPRESSION (MPA)
C         ENRM =YOUNG'S MOD./INITIAL YOUNG'S MOD.
C         PEFF =AXIAL STRESS/2 + EFFECTIVE STRESS
C         QEFF =AXIAL STRESS/2
C       TEST PARAMETERS
C         TEST =TEST NAME (MAX.=40 ALPHA-NUMERIC CHARACTERS)
C         TESTN=TEST NUMBER (MAX.=16 ALPHA-NUMERIC CHARACTERS)
C         DATE =DATE (MO/DA/YR)
C         SOIL =SOIL TYPE (MAX.=40 ALPHA-NUMERIC CHARACTERS)
C         NDP  =NUMBER OF DATA POINTS IN TEST (MAX.=100)
C         OPER =OPERATOR:S NAME (MAX.=16 ALPHA-NUMERIC CHARACTERS)
C         LCT  =NUMBER OF DATA LINES
C         NP   =NUMBER OF PAGES REQUIRED FOR DATA REDUCTION
C         NSETS =NUMBER OF TIMES PROGRAM IS TO BE RUN (MAX=9)
C
C
      INTEGER NDP,LCT,NP,OD
      REAL LRI,LCF,LR(100),L(100),OPER,LCFA,MA,JA,MMF,KO,LCFM
      DIMENSION TEST(10),OPER(4),SOIL(10),TESTN(4),DATE(2),TIME(100)
      DIMENSION CP(100),EFFST(100),CRRMS(100),TORMS(100)
      DIMENSION PEFF(100),QEFF(100),ENRM(100)
      DIMENSION  ALR(100),BR(100),FSYS(100),AS(100)
      DIMENSION V(100),VR(100),SO(100),CYC(100),SS(100),G(100),DIA(100)
      DIMENSION DR(100),PSR(100),MN(100)
      COMMON /VALS/P,T,ADF,MMF,JPA,AMP,D,F,SF/MAP/MAL/ALARM/KALARM
C
C
C    SETTING INPUT AND OUTPUT DEVICE CODES
C
      ID=5
      OD=6
C
    5 FORMAT(10A4,10A4)
   10 FORMAT(2A4,4A4,4A4)
   15 FORMAT(5F8.0)
   20 FORMAT(F8.2,3F8.3,F8.2)
   25 FORMAT(2F8.2,2F8.4)
   30 FORMAT(F8.3,2F8.2,I3)
   40 FORMAT(9F8.0)
   50 FORMAT(1H1,5X,42 HHARDIN TORSIONAL RESONANT COLUMN APPARATUS /20X
     1,54HPROGRAMMED BY DR. VINCENT P. DRNEVICH AND TERRI LORENZ/37X,23H
     2PROGRAM DATE JULY, 1978/20X,54HREVISED FOR SAMPLE DIST. RESEARCH P
     3ROJ. BY S.H. BICKEL/38X,27HREVISION DATE JANUARY, 1979///18X,30HRE
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    4SONANT COLUMN DATA REDUCTION)                                      RC601070
   55 FORMAT(1H ,2X,11HTEST NAME: ,10A4/3X,18HSOIL DESCRIPTION: ,10A4///RC601080
     12X,12H TEST DATE: ,2A4,11X,26H TEST NAME AND/OR NUMBER: ,4A4/2X,11RC601090
     2H OPERATOR: ,4A4///)                                              RC601100
   65 FORMAT(1H ,3X,30H APPARATUS CALIBRATION FACTORS,12X,23H SYSTEM CHARC601110
     1RACTERISTICS//)                                                   RC601120
   80 FORMAT(1H ,1X,11HBUR. C.F. =,F7.3,1X,5HUNITS,14X,17HAX. LOAD C.F. RC601130
     1 =,F8.4,1X,12HNEWTONS/UNIT )                                      RC601140
   85 FORMAT(1H ,1X,11HBRI       =,F7.2,1X,5HUNITS// )                  RC601150
   90 FORMAT(1H ,1X,11HJA        =,F7.5,1X,37HKG-M**2             PRESS. RC601160
     1C.F.       =,F7.3,1X,8HKPA/UNIT)                                  RC601170
   92 FORMAT(1H ,1X,11HRCFA*F**2 =,F7.2,1X,18H(RAD/VRMS)*(HZ)**2,1X,17HLRC601180
     1ENGTH CHG. C.F.=,F7.3,1X,7HMM/UNIT )                              RC601190
   94 FORMAT(1H ,1X,11HADCT      =,F7.5,1X,10HKG-M**2-HZ,9X,18HINIT. LENRC601200
     1GTH RDG =,F7.3,1X,5HUNITS )                                       RC601210
   96 FORMAT(1H ,1X,11HTCF       =,F7.4,1X,37HN-M/VRMS            NO. OF RC601220
     1DATA PTS. =,4X,I3)                                                RC601230
  100 FORMAT(1H ,23X,24HSPECIMEN CHARACTERISTICS//)                     RC601240
  102 FORMAT(1H ,1X,16HMASS            =,F7.5,1X,32HKG           DEGREE OFRC601250
     1 SAT.     =,F6.2,2H %)                                            RC601260
  103 FORMAT(1H ,1X,16HDIAMETER        =,F7.5,1X,29HM            MASS DENSRC601270
     1ITY     =,F10.1,1X,7HKG/M**3)                                     RC601280
  104 FORMAT(1H ,1X,16HLENGTH          =,F7.5,1X,32HM            VOID RATIRC601290
     1O          =,F6.3)                                                RC601300
  106 FORMAT(1H ,1X,16HSPECIFIC GRAV. =,F5.3,15X,20HROTATIONAL INERTIA =RC601310
     1)                                                                 RC601320
  108 FORMAT(1H ,1X,16HWATER CONTENT  =,F6.2,2X,1H%,28X,F10.7,1X,6HK-M**RC601330
     12)                                                                RC601340
  110 FORMAT(1H0,1X,11HINPUT DATA://16X,61HCELL    EFF.    AXIAL    LENGTRC601350
     1H    BUR     CUR.   ACCEL.   RES.  /8X,70HTIME    PRESS.  STRESS    LRC601360
     2OAD     RDG.     RDG.     RDG.     RDG.    FREQ.    /77H LINE  (MIN)  RC601370
     3 (KPA) (UNITS) (UNITS)  (UNITS) (UNITS) (V-RMS) (V-RMS)   (HZ))  RC601380
  120 FORMAT(1H    ,I4,1X,F7.2,1X,F7.2,1X,F7.3,1X,F7.3,1X,F8.3,1X,F7.3,1RC601390
     1X,F7.4,1X,F7.3,1X,F7.2)                                          RC601400
  130 FORMAT(1H0,1X,16HCALCULATED DATA://4X,68H          AX.  EFF. PRIN. RC601410
     1 VOID   SHEAR  SHEAR DAMP. ENORM  P      Q/6X,69HTIME  STR. CONF.RC601420
     2 STR.  RATIO  STRAIN   MOD. RATIO        EFF.   EFF./1X,75HLINE (RC601430
     3MIN) (%) (KPA) RATIO            (%)    (MPA)  (%)         (KPA)  (KRC601440
     4PA))                                                              RC601450
C                                                                       RC601460
  140 FORMAT(1H ,I3,1X,F6.1,1X,F4.2,1X,F6.2,1X,F4.2,1X,F6.4,1X,F7.5,1X,FRC601470
     16.2,1X,F5.2,1X,F6.4,1X,F6.2,1X,F6.2)                             RC601480
C                                                                       RC601490
C    TEST IDENTIFICATION INPUT                                          RC601500
C                                                                       RC601510
    1 READ(ID,5,END=999) (TEST(I),I=1,10),(SOIL(I),I=1,10)              RC601520
    6 READ(ID,10) DATE(1),DATE(2),(TESTN(I),I=1,4),(OPER(I),I=1,4)      RC601530
C                                                                       RC601540
C   APPARATUS CALIBRATION FACTOR INPUT                                  RC601550
C                                                                       RC601560
      READ(ID,15)JA,RCFA,ADCT,TCF,FDEV                                  RC601570
C                                                                       RC601580
C   SYSTEM CALIBRATION FACTOR INPUT                                     RC601590
C                                                                       RC601600
```

```
      READ(ID,25)LCFM,BCF,PCF,ALCF
C
C   SPECIMEN PARAMETER INPUT
C
      READ(ID,20)W,SD,SL,SG,WC
C
C    INITIAL AXIAL LOAD, BURETTE, LENGTH READING, AND NUMBER OF DATA
C    SETS INPUT
C
      READ(ID,30)ALI,BRI, LRI, NDP
C
C   TEST DATA INPUT
C
      READ(ID,40)(TIME(I),CP(I),EFFST(I),ALR(I),LR(I),BR(I),CRRMS(I),TOR
     1MS(I),FSYS(I),I=1,NDP)
      DO 145 I=1,NDP
  145 CP(I)=(CP(I)/1.02)*100.
      LCT=0
      NP=1
C
C   WRITE TITLES
C
      WRITE(OD,50)
      WRITE(OD,55)(TEST(I),I=1,10),(SOIL(I),I=1,10),DATE(1),DATE(2),(TES
     1TN(I),I=1,4),(OPER(I),I=1,4)
C
C  CALCULATION OF SPECIMEN CHARACTERISTICS
C
      PI=3.14159
      SL=SL/1000.
      SD=SD/1000.
      LCF=LCFM/1000.
      W=W/1000.
      VOL=0.25*(SD**2)*PI*SL
      UM=W/VOL
      WSOL=W/(1.+0.01*WC)
      UWAT=1000.
      VSOL=WSOL/(SG*UWAT)
      SPVR=(VOL-VSOL)/VSOL
      WWAT=W-WSOL
      VWAT=WWAT/UWAT
      SAT=VWAT/(VOL-VSOL)*100.
      SINR=W*(SD**2)/8.
      KO = 4*PI**2*FDEV**2*JA
C
C  WRITE APPARATUS, SYSTEM, AND SPECIMEN CHARACTERISTICS - WITH HEADINGS
C
      WRITE(OD,65)
      WRITE(OD,80)BCF,ALCF
      WRITE(OD,90)JA,PCF
      WRITE(OD,92)RCFA,LCFM
      WRITE(OD,94)ADCT,LRI
      WRITE(OD,96)TCF,NDP
      WRITE(OD,85)BRI
```

```
      WRITE(OD,100)
      WRITE(OD,102)W,SAT
      WRITE(OD,103)SD,UM
      WRITE(OD,104)SL,SPVR
      WRITE(OD,106)SG
      WRITE(OD,108)WC,SINR
C
C   WRITE HEADINGS FOR INPUT DATA
C
  200 CONTINUE
   45 WRITE(OD,50)
      WRITE(OD,55)(TEST(I),I=1,10),(SOIL(I),I=1,10),DATE(1),DATE(2),(TES
     1TN(I),I=1,4),(OPER(I),I=1,4)
      WRITE(OD,110)
C
C   WRITE INPUT DATA
C
      IF(NP.EQ.1) ISTART=1
      IF(NP.GT.1) ISTART=LCT+1
      IF(NP.EQ.1) ISTOP=15
      IF(NP.GT.1) ISTOP=15*NP
      IF(ISTOP.GT.NDP) ISTOP=NDP
      DO 250 I=ISTART,ISTOP
      LCT=I
      WRITE(OD,120)LCT,TIME(I),CP(I),EFFST(I),ALR(I),LR(I),BR(I),CRRMS(I
     1),TORMS(I),FSYS(I)
  250 CONTINUE
C   WRITE TITLES FOR CALCULATED DATA
C
      WRITE(OD,130)
C
C   CALCULATION OF INSTANTANEOUS VALUES OF LENGTH,AXIAL STRAIN,VOLUME,
C   VOID RATIO,EFFECTIVE CONFINING PRESSURE, AND CYCLES OF VIBRATION
C
      DO 300 I=ISTART,ISTOP
      L(I)=SL+(LRI-LR(I))*LCF
      AS(I)=((SL-L(I))/SL)*100.
      DVOL=(BRI-BR(I))*BCF/10.**6
      IF(DVOL.EQ.0.) DVOL=AS(I)*3.*VOL/100.
      V(I)=VOL-DVOL
      VR(I)=SPVR-((VOL-V(I))/VSOL)
      SO(I)=EFFST(I)*PCF
      IF(I.NE.1) GO TO 280
      DTIME=TIME(1)
      GO TO 290
  280 DTIME=TIME(I)-TIME(I-1)
  290 CYC(I)=FSYS(I)*DTIME*60.
  300 CONTINUE
C
C   CALCULATION OF DIMENSIONLESS FREQUENCY, MODULUS, DAMPING, MODE
C   SHAPE FACTOR, STRAIN AMPLITUDE, P-EFFECTIVE, Q-EFFECTIVE,
C   YOUNG'S MODULUS, INITIAL YOUNG'S MODULUS, AND NORMALIZED RATIO
      JPA = 0
      P = 1000.
```

```
      DO 400 I=ISTART,ISTOP
      DIA(I)=SQRT(4.*V(I)/(L(I)*PI))
      AXLD=(ALR(I)+ALI)*ALCF
      AXS=4*AXLD/(1000.*(PI)*(DIA(I))**2)
      PEFF(I)=AXS/2.+SO(I)
      QEFF(I)=AXS/2.
      PSR(I)=(SO(I)+AXS)/SO(I)
      SO(I)=SO(I) + AXS/3.
      WT=W-UWAT*(BRI+BR(I))*BCF/10.**6
      RHO=WT/V(I)
  320 SINR=WT*DIA(I)*DIA(I)/8.
      T = (JA/SINR)*(1-(FDEV/FSYS(I))**2)
      ADF=ADCT/(2.*PI*FSYS(I)*SINR)
      MMF=(RCFA*TORMS(I)/(TCF*CRRMS(I)))*SINR*(2.*PI)**2
      CALL RCSUB
      IF(MAL.NE.0.OR.KALARM.NE.0)GO TO 400
      G(I)=(RHO*(2.*PI*L(I))**2)*(FSYS(I)/F)**2/10.**6
      DR(I)=D
      SS(I)=(RCFA/(FSYS(I)**2))*TORMS(I)*SF*(DIA(I)/(3.*L(I)))*100.
      EMAX=G(I)*3.
      IF(AS(I).NE.0.)GO TO 350
      E=EMAX
      GOTO 360
  350 E=AXS/(10.*AS(I))
  360 ENRM(I)=E/EMAX
  400 CONTINUE
C
C   WRITE CALCULATED DATA
C
      DO 500 I=ISTART,ISTOP
      LCT=I
      WRITE(OD,140)LCT,TIME(I),AS(I),SO(I),PSR(I),VR(I),SS(I),G(I),DR(I)
     1,ENRM(I),PEFF(I),QEFF(I)
  500 CONTINUE
      LCT=ISTOP
      IF(ISTOP.EQ.NDP) GO TO 600
      NP=NP+1
      GO TO 45
  600 GO TO 1
  999 STOP
      END
```

SEE APPENDIX A. FOR THE SUBROUTINE RCSUB.

```
10 REM  TRIAXA.KA  DATA ACQUISITION PROGRAM FOR UNDRAINED TRIAXIAL
30 REM     TESTS WHERE CELL PRESS.-PORE PRESS. IS MEASURED.
50 REM  WRITTEN BY V.P. DRNEVICH, APRIL 11, 1975
90 REM  REVISED FOR PROGRAMMABLE REAL TIME CLOCK, 07/15/76
105 REM  REVISED TO RUN SEGMENTS OF TEST S BICKEL 1/3/79
110 REM  CHARACTERISTICS OF THE PROGRAM:
130 REM     DEFORMATION TRANSDUCER CONNECTED TO CHANNEL NO. 1
150 REM     LOAD TRANSDUCER CONNECTED TO CHANNEL NO. 2
170 REM     PORE PRESSURE TRANSDUCER CONNECTED TO CHANNEL NO. 3
190 REM     START-STOP SW. W/OUTPUT > 0.8 VOLT CONNECTED TO CHAN.NO.0
210 REM     RDGS. TAKEN AT EQUAL INTERVALS OF TIME
230 REM     INIT. DEFORM. RDGS. SUBTRACTED FROM ALL SUBSEQUENT DEF. RDGS.

250 REM     IF DESIRED, ALL DATA ARE WRITTEN INTO A FILE THAT IS LABELED
270 REM       WITH THE TEST DESIGNATION AND EXTENSION ".FF".
290 DIM B$(15),C$(15),D$(15),F1$(10),F$(15),T$(68),U$(68),V$(45),W$(40)
310 DIM A(100),B(100),C(100),D(100),E(100),P(100),P1(100),T(100)
330 DIM G$(19),H$(40),O$(15),I$(100,72)
350 UDEF INI(N),PLY(Y),DLY(N),DIS(S,E,N,X)
370 UDEF SAM(C,N,P,T),CLK(R,O,S),CLW(N),ADC(N)
371 PRINT"DO YOU NEED HELP TO RUN THIS PROGRAM (Y=YES, N=NO)";
372 INPUT X$
373 IF X$="N" THEN 396
374 O$="DTA1:TRIAX.HH"
375 FILE#1:O$
376 INPUT#1:R,C,L
377 FOR X=1 TO R
378 INPUT#1:I$(X)
379 NEXT X
380 CLOSE#1
381 PRINT\PRINT
382 FOR S=1 TO R
383 PRINT I$(S)
384 NEXT S
385 O$="DTA1:TRIAX.HE"
386 FILE#1:O$
387 INPUT#1:R,C,L
388 FOR X=1 TO R
389 INPUT#1:I$(X)
390 NEXT X
391 CLOSE#1
392 FOR S=1 TO R
393 PRINT I$(S)
394 NEXT S
395 INPUT A9
396 PRINT
397 PRINT
400 PRINT"TRIAXIAL COMPRESSION TEST DATA ACQUISITION PROGRAM"
410 PRINT"TYPE TEST AND SPECIMEN INFORMATION AS REQUESTED"
430 PRINT"INPUT TEST DESIGNATION (6 SYMBOLS MAX.)";\INPUT A$
450 PRINT"OPERATOR";\INPUT B$
470 PRINT"DATE";\INPUT C$
490 PRINT"SOIL TYPE";\INPUT D$
510 PRINT"SPECIMEN INFORMATION"\PRINT"NO. OF DIAMETERS";\INPUT B2\C2=0
```

```
530 PRINT"DIAMETERS IN CM.";\FOR K=1 TO B2\INPUT D2\C2=C2+D2\NEXT K
550 C2=C2/B2
570 PRINT"NO. OF LENGTHS";\INPUT B3\C3=0
590 PRINT"INPUT LENGTHS IN CM.";\FOR K=1 TO B3\INPUT D3\C3=C3+D3\NEXT K
610 C3=C3/B3
630 A3=C2*C2*3.14159*C3/4.
650 PRINT"WEIGHT IN GRAMS";\INPUT A4\PRINT "MOIS. CONTENT IN PERCENT";
670 INPUT B4\PRINT"SPECIFIC GRAVITY";\INPUT C4
690 PRINT"CALIBRATION DATA"
710 PRINT"DEF. CAL. FACT. IN CM./VOLT (NORM. VAL. = 5.08)";\INPUT A6
730 PRINT"LOAD CAL.FACT.IN NEWTONS/VOLT (NORM.VAL.= 2224.)";\INPUT B6
750 PRINT"PRESSURE TRANS.CALIB.FACT.IN MPA/VOLT (NORM.VAL.=0.6895)";
770 INPUT C6\REM PRESS. CAL. FAC.
790 PRINT"DATA RDG. INTERVAL IN MINUTES";\INPUT T6\T3=T6-0.03
810 PRINT"STOP TIME IN MINUTES (MAX. = 99*RDG. INT.)";\INPUT S0
820 PRINT "INITIAL DEFORMATION VOLTAGE READING";\INPUT A9
825 PRINT "INITIAL PRESSURE READING";\INPUT Z0
830 G$="RDG.NO. TIME(MIN) "
850 H$="DEF. (CM)    FORCE (N) E.STRESS(MPA)"
870 PRINT\PRINT G$;H$;" USE START SW. TO BEGIN"
890 T9=ADC(0)
910 IF T9>400 GO TO 930\IF T9<-400 GO TO 930\GO TO 890
930 T0=0\T2=0.\REM INITIALIZE RDG. NO. AND TIME
950 A(T0)=ADC(1)
951 B(T0)=ADC(2)
953 IF A9=0 THEN 955
954 GO TO 956
955 A9=A(T0)
956 A(T0)=A(T0)-A9
957 PRINT\PRINT "INITIAL DEFORM. VOLTAGE RDG.:";A9\PRINT
970 P(T0)=ADC(3)\REM  PRESS. RDG.
975 IF P(T0)=0 THEN 980\GO TO 990
980 P(T0)=.0001
990 GO TO 1230
1010 T1=0.\T7=0.
1030 S9=S0/T6\IF T0=S9 THEN 1380
1050 Y=CLK(3,600,0)
1070 Y=CLW(0)
1090 T1=T1+1\T7=T1/100.\IF T7 < T3 THEN 1070
1110 T0=T0+1\REM RDG. NO.
1130 T2=T2+T6\REM TIME IN MINUTES\T(T0)=T2
1150 IF T2>S0 GO TO 1380
1170 T9=ADC(0)\A(T0)=ADC(1)\B(T0)=ADC(2)\A(T0)=A(T0)-A9
1190 P(T0)=ADC(3)
1195 IF P(T0)=0 THEN 1200\GO TO 1210
1200 P(T0)=.0001
1210 IF T9>400 GO TO 1250\IF T9<-400 GO TO 1250\GO TO 1380
1230 IF A(T0)<0 GO TO 1250\A(T0)=A(T0)*A6/511\GO TO 1270
1250 A(T0)=A(T0)*A6/512
1270 IF B(T0)<0 GO TO 1290\B(T0)=B(T0)*B6/511\GO TO 1330
1290 B(T0)=B(T0)*B6/512
1310 IF P(T0)<0 GO TO 1330\P(T0)=P(T0)*C6/511\GO TO 1350
1330 P(T0)=P(T0)*C6/512
1350 T2=INT(T2*10^3+.5)/10^3
```

```
1355 PRINT TAB(2);(T0+1);TAB(10);T2;TAB(19);A(T0);TAB(31);B(T0);TAB(43);

1356 PRINT P(T0)
1370 GO TO 1010
1380 PRINT"TYPE 1, LINE FEED TO TOP OF NEXT PAGE, HIT RETURN.";
1385 INPUT A9
1390 PRINT\PRINT\PRINT
1395 A2=A3/C3
1400 A5=A4/A3
1405 B5=A5/(1+B4/100)
1410 C5=C4/B5-1
1415 PRINT"UNIVERSITY OF KENTUCKY SOIL MECHANICS LABORATORY"
1420 PRINT"            TRIAXIAL COMPRESSION TEST"
1425 PRINT
1430 PRINT"TEST INFORMATION"
1435 PRINT"TEST NUMBER:";A$
1440 PRINT"OPERATOR:";B$
1445 PRINT"DATE:";C$
1450 PRINT"SOIL TYPE:";D$
1455 PRINT"SPECIMEN INFORMATION"
1460 PRINT"AVERAGE DIAMETER = ";C2;" CM"
1465 PRINT"AVERAGE LENGTH = ";C3;" CM"
1470 PRINT"WEIGHT = ";A4;" GRAMS"
1475 PRINT"VOLUME = ";A3;" CUBIC CM"
1480 PRINT"MOISTURE CONTENT = ";B4;"%"
1485 PRINT"SPECIFIC GRAVITY = ";C4
1490 PRINT"WET DENSITY = ";A5;" GRAMS/CUBIC CM"
1495 PRINT"DRY DENSITY = ";B5;" GRAMS/CUBIC CM"
1500 PRINT"VOID RATIO = ";C5
1505 PRINT"CALIBRATION DATA"
1510 PRINT"DEFORMATION CALIBRATION FACTOR = ";A6;" CM/VOLT"
1515 PRINT"FORCE CALIBRATION FACTOR = ";B6;" NEWTONS/VOLT"
1520 PRINT"PRESSURE CALIBRATION FACTOR = ";C6;" MPA/VOLT"
1525 PRINT\PRINT
1530 T$="TIME  DEFORM.   A-PP    EFF.STRESS  OBLIQUITY"
1535 U$="  P-EFF    Q-EFF    STRAIN"
1540 V$="(MIN)  (CM.)   COEFF.    (MPA)    (UNITLESS)"
1545 W$="  (MPA)     (MPA)     (%)"
1550 PRINT T$;U$
1555 PRINT V$;W$
1558 C9=T0
1560 FOR I=0 TO C9
1565 C(I)=A(I)*100./C3
1570 D(I)=A2/(1.-C(I)/100.)
1575 E(I)=(B(I)/D(I)/20.)/10
1580 P1(I)=P(I)+E(I)
1585 D(I)=(P1(I)+E(I))/(P1(I)-E(I))
1590 C(I)=INT(C(I)*10^4+0.5)/10^4
1595 D(I)=INT(D(I)*10^4+0.5)/10^4
1600 E(I)=INT(E(I)*10^4+0.5)/10^4
1605 P1(I)=INT(P1(I)*10^4+0.5)/10^4
1610 A(I)=INT(A(I)*10^4+0.5)/10^4
1613 T(I)=INT(T(I)*10^3+0.5)/10^3
1615 IF Z0<>0 THEN 1617
```

```
1616 Z0=P(0)
1617 P9=Z0
1620 B(I)=(P9-P(I))/(2.*E(I)+.0001)
1625 B(I)=INT(B(I)*10^4+0.5)/10^4
1628 P(I)=INT(P(I)*10^5+0.5)/10^5
1630 PRINT T(I);TAB(7);A(I);TAB(15);B(I);TAB(26);P(I);TAB(37);D(I);
1635 PRINT TAB(47);P1(I);TAB(56);E(I);TAB(65);C(I)
1640 NEXT I
1645 PRINT
1650 PRINT
1655 PRINT"DO YOU WISH TO STORE RESULTS (Y=YES,N=NO)";
1660 INPUT Q$
1665 IF Q$="N" THEN  1780
1670 PRINT"STORE RESULTS ON DISK OR TAPE (D OR T)";
1675 INPUT J$
1680 IF J$="D" THEN 1700
1685 IF J$="T" THEN 1710
1690 PRINT"WRONG INPUT. D OR T ONLY!"
1695 GO TO 1670
1700 F1$="RXA1:"
1705 GO TO 1715
1710 F1$="DTA1:"
1715 F2$=".FF"
1720 F$=F1$&A$&F2$
1725 FILEV#1:F$
1730 PRINT#1:A$
1735 PRINT#1:B$\PRINT#1:C$\PRINT#1:D$\PRINT#1:(C9+1)
1740 PRINT#1:C2,C3,A3,A4
1742 PRINT#1:B4,C4,A6,B6,C6
1745 PRINT#1:A5,B5,C5
1750 FOR K=0 TO C9
1755 PRINT#1:T(K),A(K),B(K),P(K)
1760 PRINT#1:C(K),D(K),E(K),P1(K)
1765 NEXT K
1770 CLOSE#1
1775 PRINT"FILE ";F$;" HAS BEEN CREATED. USE TRIAX.CY TO RECALL"
1780 PRINT"DO YOU WISH TO RUN AGAIN (Y=YES,N=NO)";
1785 INPUT Q$
1790 IF Q$="N" THEN 1850
1795 PRINT"TYPE 1, LINE FEED TO TOP OF NEXT PAGE, HIT RETURN.";
1800 INPUT A9
1805 GO TO 10
1850 END
```

APPENDIX E: NOTATION

a_1, a_2, a_3	Coefficients in Equation (35)
B	Skempton pore pressure coefficient
c'	Cohesion in terms of effective stress
e	Void ratio
e_i	Void ratio for initial state of stress
G_{max}	Initial tangent shear modulus
$(G_{max})_i$	Initial tangent shear modulus for initial state of stress
H	Inverse of slope of the secant connecting the initial stress point and any other stress point
H_f	Value of H where other stress point corresponds to failure
I.D.	Inside diameter
K	Coefficient in Hardin Equation that depends on plasticity index
K_f	Line on stress path diagram associated with Mohr-Coulomb failure
K_o	Coefficient of lateral earth pressure at rest
LVDT	Linear varying differential transformer displacement transducer
OCR	Overconsolidation ratio
p'	Stress path abscissa in terms of effective stress
p_a	Atmospheric pressure
p'_i	Stress path abscissa for initial state of stress
p'_j	Stress path abscissa corresponding to stress point j
PI	Plasticity Index in percent
q	Stress path ordinate
q_f	Stress path ordinate corresponding to state of failure
q_j	Stress path ordinate corresponding to stress point j
S_u	Undrained shear strength

T	T/T_{max}
V	Specimen volume
ΔV	Change in specimen volume
γ	Shear strain
γ_j	Shear strain at stress path point j
γ_r	Reference strain given by T_{max}/G_{max}
$\Delta\gamma$	Shear strain increment
$\Delta(\gamma/\gamma_r)_j$	Incremental normalized shear strain at stress path point j
ε	Axial strain
ε_{axial}	Axial strain in triaxial test associated with σ_{axial}
ε_j	Axial strain at stress path point j
ε_r	Radial strains in triaxial test
$(\varepsilon_r)_j$	Radial strain in triaxial test at stress path point j
σ_{axial}	Axial stress in triaxial test in addition to initial state of stress
σ'_o	Mean effective confining stress
σ'_1, σ'_2, σ'_3	Principal stresses in terms of effective stress
$(\sigma'_1)_i$, $(\sigma'_2)_i$, $(\sigma'_3)_i$	Effective principal stresses for initial state of stress
σ'_v	Effective overburden stress
T	Shear stress
T_{max}	Maximum shear stress applied in addition to initial shear stress
$\emptyset'$	Angle of shearing resistance in terms of effective stress

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Drnevich, Vincent Paul
Evaluation of sample disturbance on soils using the concept of "reference strain" / by Vincent P. Drnevich, Civil Engineering Department, University of Kentucky, Lexington, Kentucky. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1979.
67, [99] p. : ill. ; 27 cm. (Technical report - U. S. Army Engineer Waterways Experiment Station ; GL-79-13)
Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C., under Contract No. DACW39-78-C-0046, Work Unit CWIS 31145.
References: p. 65-67.

1. Reference strain. 2. Resonant column tests. 3. Sample disturbance. 4. Shear modulus. 5. Shear strain. 6. Shear stress. 7. Stress-strain curves. 8. Triaxial shear tests. I. Kentucky. University. Dept. of Civil Engineering. II. United States. Army. Corps of Engineers. III. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Technical report ; GL-79-13.
TA7.W34 no.GL-79-13